Attorney Docket No.: 21040-000300US

PATENT APPLICATION

INTEGRATED PLANAR COMPOSITE COUPLING STRUCTURES FOR BI-DIRECTIONAL LIGHT BEAM TRANSFORMATION BETWEEN A SMALL MODE SIZE WAVEGUIDE AND A LARGE MODE SIZE WAVEGUIDE

Inventors:

Yan Zhou, a citizen of Singapore, residing at,
4445 Valley Ave., Apt. E
Pleasanton, CA 94566

Seng-Tiong Ho, a citizen of USA, residing at,
120 Picardy Lane
Wheeling, IL 60090

Assignee:

Phosistor Technologies, Incorporated
7079 Commerce Circle
Pleasanton, CA 94588

Entity: Small

TOWNSEND and TOWNSEND and CREW LLP
Two Embarcadero Center, 8th Floor
San Francisco, California 94111-3834
Tel: (415) 576-0200

INTEGRATED PLANAR COMPOSITE COUPLING STRUCTURES FOR BI-DIRECTIONAL LIGHT BEAM TRANSFORMATION BETWEEN A SMALL MODE SIZE WAVEGUIDE AND A LARGE MODE SIZE WAVEGUIDE

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims priority from co-pending U.S. Provisional Patent Application No. 60/242,213, filed October 20, 2000, entitled MULTIPORT INTEGRATED COUPLER FOR BI-DIRECTIONAL LIGHT BEAM TRANSFORMATION BETWEEN A SMALL SIZE WAVEGUIDE AND A LARGE SIZE WAVEGUIDE, which is hereby incorporated by reference, as if set forth in full in this document, for all purposes.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates, in general, to optical structures that enable optical beam transformation between a large-mode-size waveguide and a small-mode-size waveguide, and methods of making the same. In particular, the present invention relates to methods for transforming the optical mode between a photonic device and one or more optical fibers. The present invention also relates, in particular, to the integrated fabrication of such structures on a module platform or the photonic device, their connections with one or more input/output optical fibers.

2. Description of the Related Art

The current strong demand for bandwidth over the Internet has resulted in great demand for photonic device components in optical communications and data or information processing. These device components include fiber optics, non-linear crystal optics, and integrated optics in such material systems as dielectrics, polymers, optical crystals, and semiconductors (also called electro-optic or optoelectronic systems).

Optical-crystal and dielectric-material-based discrete optical components such as $LiNbO_3$-based-modulators, glass ion-exchange-based optical power splitters and flame-hydrolysis-deposited silica-on-silicon multiplexers/demultiplexers, can play certain roles, but their sizes are generally large and their functions are limited. Hence, in the long run, it is very unlikely that they can compete with waveguide based photonic devices such as Photonic

Integrated Circuits (PICs), which can be made very small and also multifunctional with high packing density similar to today's large scale integration of microelectronic circuits.

Waveguides are used for inputting and out putting light energy for such photonic devices to optical fibers. The input/output waveguides in a photonic device are typically made up of dielectric or semiconductor materials. A photonic device may contain one or more such input/output waveguides. Unless otherwise specified, such input/output optical waveguides will be referred to as device waveguides below.

In spite of the promise of waveguide based photonic devices, in general, and photonic integrated circuits, in particular, however, several challenges remain. One challenge is at the optical interface. Light must be efficiently coupled, with high precision and stability, between drastically dissimilar components and materials, in a cost effective, manufacturable way. There are several issues that need to be addressed with respect to this challenge, including the following:

(1) The drastically different spot or mode profile in terms of size and symmetry between a fiber and a photonic device waveguide.

(2) The difficulty in the alignment of a fiber and a photonic device waveguide, as well as of any other intermediate component such as a ball lens.

(3) The difficulty of coupling multiple fibers to a photonic device with multiple device waveguides efficiently in a cost effective way.

Prior-art efforts addressing each of these challenges are summarized below.

<u>(1) Prior art in dealing with the mode-size conversion issue</u>

With regard to mode-size conversion, in order to ensure single-mode operation (as required for high-speed, large-capacity optical signal manipulation), the dimension of a device waveguide is typically one order of magnitude less than that of a silica fiber waveguide. The result is a substantial mode-field mismatch between these two waveguides. As shown in Figure 1(a) and (b), for optimal performance, the mode profile of a single-mode optical fiber **110** is circular, and its size is generally about 5 to 10 μm in diameter, whereas the mode profile of a photonic device waveguide **120** is elliptical and its dimension is typically less than 1 to 3 μm — as small as 0.2 μm for high-density photonic integrated circuits.

Various methods are currently used for transforming the optical modes between an optical fiber and a device waveguide. These methods are broadly summarized below.

Method 1 – Butt-coupling method

The simplest coupling arrangement is a direct butt-joining between a fiber and a semiconductor laser (or other semiconductor waveguide) as shown in Fig. 2. Since light is only required to couple in one direction — i.e., from the laser **210** to the fiber **220** — one can adjust the gap distance **230** to allow the divergent cone of light **240** to expand and roughly match the size of a fiber core **250**. One problem with this approach is the relatively low coupling efficiency caused by the large divergence angle and the fact that a fiber can only capture and guide a narrower cone of light within a small capturing angle. As a result, the typical coupling efficiency for a direct butt-joining is less than 5-30% depending on the size of the device waveguide. In spite of the low coupling efficiency, this technique is being explored by NEC of Japan (among others) for low-cost mass packaging of transceivers because this technique requires the fewest of components, which minimizes component cost. (Kenji Yamauchi et al., "Automated mass production line for optical module using passive alignment technique," 50th Electronic Components and Technology Conference, May 21-24, 2000, Las Vegas, Nevada, USA).

Method 2 – Lensed fiber or microlens method

A method improved over the direct butt-joining technique is to make the fiber end into a lens **310** (lensed fiber) as shown in Fig. 3 so that more light can be captured by the fiber. (Kazuhiko Kurata, "Mass production techniques for optical modules," 48th Electronic Components and Technology Conference, May 27-28, 1998, Seattle, Washington, USA). Another improved method uses a separate lens **410** placed in the gap **420** as shown in Fig. 4. Various lenses have been used, including glass ball lenses and GRIN (graded refractive index) rod lenses, as well as aspheric injection molded plastic lenses. (Keith Anderson, "Design and manufacturability issues of a co-packaged DFB/MZ module," 49th Electronic Components and Technology Conference, June 2-4, 1999, San Diego, California, USA). With these lenses, the coupling efficiency is increased to 50% to 70% for device waveguide mode about 2 μm in size.

Method 3 – Cylindrical lenses method

Besides geometric discontinuities between a device waveguide and an optical fiber, the imperfect coupling efficiency results also in part from the elliptical shape of the

light cone emerging from a typical device waveguide such as that from a Fabry-Perot cavity semiconductor laser, which causes a non-perfect match with the circular mode pattern of the fiber. A method to correct for such elliptical or astigmatic beam shape is shown in Fig. 5, which illustrates the use of a combination of two perpendicular cylindrical lenses **510** and **520** of different focusing powers along the vertical lens (**510**) and lateral lens (**520**) directions, which can circularize the elliptical beam and theoretically increase the coupling efficiency to about 85% for a typical semiconductor laser with a mode size of about 1 μm (vertical) by 3 μm (horizontal). (Sun-Yuan Huang et al., "High coupling optical design for laser diodes with large aspect ratio," 49th Electronic Components and Technology Conference, June 2-4, 1999, San Diego, California, USA).

Method 4 – Cylindrical lensed fiber method

A cylindrical lensed fiber (CLF) has also been used. (Soon Jang "Automation manufacturing systems technology for opto-electronic device packaging" 50th Electronic Components and Technology Conference, May 21-24, 2000, Las Vegas, Nevada, USA). Although the coupling efficiency with the use of a CLF can be high (~ 90%), the cost is also high because a CLF is not easy to make, and achieving high coupling efficiency also requires difficult labour-intensive alignment, as a practical matter.

Method 5 – Laterally tapered rectangular waveguide on top of a large rectangular waveguide method

Another approach to mode-size conversion is to place a laterally tapered rectangular waveguide on a large mode size rectangular waveguide, where light coupling between the top and the bottom waveguide occurs as a result of the top lateral taper. This method can serve the function of mode-size conversion in both the vertical and horizontal directions, but it is not well accepted in practice due to the difficulty in integrating such a structure with a device waveguide and also the cost of manufacturing such a structure. Figure 6 shows such a polymer based waveguide structure **610** inserted between a semiconductor laser **620** and a fiber **630**. (D. J. Goodwill et al., "Polymer tapered waveguides and flip-chip solder bonding as compatible technologies for efficient OEIC coupling," 47th Electronic Components and Technology Conference (ECTC), May 18-21 1997, San Jose, California, USA). One difficulty in this approach is the integration of such a tapered waveguide **610** made of polymer with a laser **620** made of semiconductor material due to the large difference in their coefficients of thermal expansion and mechanical stabilities. In the case where such a structure is made of the same semiconductor material as that of the semiconductor laser, it

would require the epitaxial growth of a large bottom waveguide layer and the cost will be high.

Method 6 – Vertically tapered down rectangular waveguide method

To enable easy integration, vertically tapered down semiconductor waveguide spot-size converters that squeeze the guided optical mode into the cladding have been integrated with semiconductor lasers. (Aaron E. Bond et al., "High speed packaged electroabsorption modulators for optical communications" 50th Electronic Components and Technology Conference, May 21-24, 2000, Las Vegas, Nevada, USA; Y. Inaba et al., "Multiquantum-well lasers with tapered active stripe for direct coupling to single mode fiber" IEEE Photonics Technology Letters, Vol. 6, pp. 722, 1997; M. Kitamura, "Method of making a tapered thickness waveguide integrated semiconductor laser," U.S. Patent No. 5,792,674, issued Aug. 11, 1998; Jeon et al., "Laser diode device having a substantially circular light output beam and a method of forming a tapered section in a semiconductor device to provide for a reproducible mode profile of the output beam," U.S. Patent No. 6,052,397, issued Apr. 18, 2000). Although this method can enlarge the optical mode in the vertical direction, Problems associated with such structures include the required length of the tapered down structure that will lead to additional light propagation loss and the additional expense of III-V semiconductor materials.

<u>2) Costs of photonic device module connection with optical fibers [problem #2]</u>

While the above-mentioned methods may be employed to transfer optical energy somewhat efficiently between an optical fiber and a device waveguide of about 2 μm in size, the approaches of these methods are costly. Typically, an enclosure is used to house the device, the discrete mode-transferring element (e.g. a ball lens), and the optical fiber, thereby forming a packaged module. To align the device waveguide to the fiber and the mode transferring module, most photonic device manufacturers are still performing manual alignment under a microscope because of the very disparate nature of the components, their high price and low product volumes. Such a process is not well suited to high-volume, low-cost production.

Existing techniques for fixing a fiber (and lens) in position with respect to a rectangular semiconductor waveguide include epoxy curing, soldering, mechanical fixture, and laser welding. In order to reduce the need for manual placement/alignment and fixing in the packaging process, efforts have been focused on automating the fixing process. For

example, Newport, JDS-Uniphase and NEC are developing automatic parts-handling and assembling procedures using machine vision combined with micro-stages or micro-robots to achieve sub-micron precision (Soon Jang, "Automation manufacturing systems technology for opto-electronic device packaging," 50th Electronic Components and Technology Conference, May 21-24, 2000, Las Vegas, Nevada, USA; Peter Mueller and Bernd Valk, "Automated fiber attachment for 980 nm pump module," 50th Electronic Components and Technology Conference, May 21-24, 2000, Las Vegas, Nevada, USA; Kazuhiko Kurata, "Mass production techniques for optical modules," 48th Electronic Components and Technology Conference, May 27-28, 1998, Seattle, Washington, USA).

At the same time, the concept of a silicon optical bench (SiOB) on which V-grooves are wet-etched to guide the mounting or placement of photonic components including fibers, lenses, and even semiconductor chips has been well accepted; SiOBs are disclosed in several U.S. patents (e.g., Murphy, "Fiber-waveguide self alignment coupler," U.S. Patent No. 4,639,074, issued Jan. 27, 1987; Albares et al,. "Optical fiber-to-channel waveguide coupler," U.S. Patent No. 4,930,854, issued June 5, 1990; Benzoni et al., "Single in-line optical package," U.S. Patent No. 5,337,398, issued Aug. 9, 1994; Francis et al., "Waveguide coupler," U.S. Patent No. 5,552,092, issued Sept. 3, 1996; Harpin et al., "Assembly of an optical component and an optical waveguide," U.S. Patent No. 5,881,190, issued Mar. 9, 1999; Roff, "Package for an optoelectronic device," U.S. Patent No. 5,937,124, issued Aug. 10, 1999). It is very likely that high precision automation will be combined with silicon V-groove technology to produce fiber-pigtailed or fiber-connectable photonic devices. The V-groove technology, however, still needs some alignment procedure.

In spite of the above-mentioned approaches, the current packaging cost is still very high. For example, about 70 to 80% of the total cost of any fiber-pigtailed III-V optoelectronic module such as an optical transceiver is due to its packaging. Moreover, most of the prior art has been aimed at solving the semiconductor-laser-to-fiber coupling problem, which is one-directional. For future dense wavelength division multiplexing (DWDM) optical communication systems, bi-directional multi-port devices like M×N switches will be in large demand, and the prior art is not able to provide an adequate solution.

<u>(3) Difficulty of current methods for multiple fiber connections [Problem #3]</u>

The current methods are somewhat adequate for large photonic device with one input/output waveguide, they generally become difficult when more than one

input/output and fibers are involved. This is because the yield for the alignment procedures referred to above rapidly decreases as the number of input and output fibers increases. This yield reduction can seriously limit the application of such coupling and packaging techniques to high-density photonic integrated circuits, for which tens to hundreds of input and output fibers are expected to be connected to a single photonic chip.

The main criteria needed for optical mode transferring methods and devices to achieve a cost-effetive and efficient optical energy transfer between a device waveguide and one or more optical fibers can be more specifically described as follows:

(i) The methods and devices should be able to achieve mode size transformation from about 10 μm down to about 2 μm (for $\lambda = 1.55$ μm) or in the reverse direction for typical waveguide devices.

(ii) The methods and devices should be able to achieve mode size transfer from about 10 μm to below 1 μm (for $\lambda = 1.55$ μm) or in the reverse direction for more challenging waveguide devices such as high-density semiconductor photonic integrated circuit.

(iii) The methods and devices should be capable of achieving self-alignment between the photonic device and the optical fibers or other intermediate beam transferring elements. Self-alignment lends itself to low-cost manufacturing. It also allows cost-effective coupling between a photonic device and more than one optical fibers.

(iv) The methods and devices should have low optical reflection and absorption losses between the photonic device and the optical fibers.

(v) The methods and devices should have the flexibility of transferring the vertical and lateral mode size separately. This allows it to correct for beam astigmatism in the device waveguide mode.

(vi) The methods and devices should have high yield and low fabrication costs.

The current mode transformation methods can not adequately achieve the majority of criterias (i) – (vi). For example, the ball lens method can achieve (i) and (iv) but not (ii), (iii), (v) and (vi)

What is still needed in the field, therefore, are devices and methods for transferring the mode size between photonic device and one or more optical fibers that satisfy some or a majority of critirias (i) to (vi) above.

The present invention described herein overcomes the various difficulties encountered by the previous methods by the use of new optical structures referred to as integrated composite coupling structures (ICCS). The mode transformation device or mode transformer is referred to as an Integrated Compoiste Mode Transformer (ICMT). With the use of the new optical structures according to the present invention, disadvantages associated with prior methods are addressed.

BRIEF SUMMARY OF THE INVENTION

The integrated composite coupling structures of the present invention provide an integrated approach to optical mode transformation. The integrated approach allows fabrication of a large number of couplers using established processes used frequently in electronics industries and photonic integrated circuit industries, thereby resulting in lower fabrication cost. The composite optical structures allow the beam to be transformed differently in the vertical and lateral directions.

An embodiment of the present invention provides a planar optical structure that can transform the vertical mode size between a photonic device and an optical fiber. The size of the optical structure is small relative to the optical fiber diameter, which reduces alignment sensitivity. In one aspect of the present invention, the vertical mode transformation is achieved via the use of a micro vertical graded refractive index (μ-VGRIN) structure that is capable of beam size transformation down to below $\lambda/1.5$ (or 1 μm for $\lambda = 1.5$ μm). Moreover, the μ-VGRIN structure can be fabricated according to the present invention using established process technology usch as Ion-Assisted-Deposition with low cost and low optical loss.

In another aspect of the present invention, a composite structure is formed by combining a μ-VGRIN structure with a horizontal taper structure to achieve separate transformation of the horizontal and vertical beam mode sizes, thereby allowing 2-D beam transformation capable of astigmatic beam size correction. The composite structure can include a cascaded or concurrent geometry.

In yet another aspect of the present invention, an integrated composite coupling structure or its composite variants is further integrated to an alignment V-groove structure for fiber on one side and a alignment platform for photonic chip on the other side to

achieve self-alignment between the photonic device, the optical fiber and the coupling structure (or its composite variants).

In yet another aspect of the present invention, a μ-VGRIN structure is combined with a micro-lateral graded refractive index (μ-LGRIN) structure to achieve separate transformation of the vertical and lateral beamsizes. The μ-LGRIN structure can be fabricated with low cost and large quantity using UV-imprinting process used in the photonic industry. The composite μ-VGRIN and μ-LGRIN structure can include a cascaded or concurrent geometry.

In yet another aspect of the present invention, a high-refractive-index-contrast vertical sharp taper (HRC-VST) and dielectric structure is used for which the relative refractive index of the vertical taper material is substantially higher than that of the dielectric material.. The high index contrast allows beam transformation down to about $\lambda/15$ (or 0.1 μm for $\lambda = 1.5$ μm) when the taper is made up of silicon and the dielectric is made up of glass. The HRC-VST can be fabricated according to the present invention using established processes in the electronics and photonics industries with low costs.

In yet another aspect of the present invention, a composite structure is formed by combining an HRC-VST structure with either a high-refractive-index-contrast laterally gradual taper (HRC-LGT) or a μ-LGRIN structure to achieve separate transformation of the vertical and lateral beam sizes thereby allowing 2-D transformations capable of astigmatic beam size correction. The composite structure can include a cascaded or concurrent geometry.

In yet another aspect of the present invention, a HRC-VST structure or a composite variant is further integrated to a V-groove structure for fiber on one side and an alignment platform for photonic chip on the other side to achieve self-alignment between the photonic device, the optical fiber and the HRC-VST structure (or its composite variants).

In yet another aspect of the present invention, the sharp taper is in the lateral/horizontal direction, resulting in a high-refractive-index-contrast lateral sharp taper (HRC-LST) which provide beam transformation in the lateral/horizontal direction.

In yet another aspect of the present invention, a plurality of μ-GRIN structures, sharp taper structures, gradual taper structures and their composite variants are further integrated to a V-groove structure for fiber on one side and an alignment platform for photonic chip on the other side to achieve self-aligned beam transformation between a photonic chip device and more than one optical fibers.

In yet another aspect of the present invention, a μ-GRIN structure or a sharp taper structure, or one of their composite variants is fabricated directly on a photonic device chip.

A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A illustrates the mode profile of a typical single-mode fiber.

Fig. 1B illustrates the mode profile of a typical single mode III-V compound semiconductor channel waveguide.

Fig. 2 shows a prior-art system in which light is transmitted directly from a semiconductor laser to a single mode optical fiber.

Fig. 3 shows a prior-art system in which light is transmitted from a semiconductor laser into a lensed optical fiber.

Fig. 4 shows a prior-art system in which light is transmitted via a lens from a semiconductor laser into an optical fiber.

Fig. 5 shows side and top views of a prior-art system in which light is transmitted via two perpendicular cylindrical lenses of different focusing powers from a semiconductor laser into an optical fiber.

Fig. 6 shows a prior-art system in which light is transmitted via a tapered polymer waveguide from a semiconductor laser into an optical fiber.

Fig. 7 shows an optical interface between two media, illustrating the principles of reflection, refraction, the critical angle, and total internal reflection.

Fig. 8 illustrates a principle of light guiding in a step-index optical fiber or waveguide.

Fig. 9 illustrates a principle of light guiding in a GRIN optical fiber or waveguide.

Fig. 10 illustrates a principle of approximating a continuous graded refractive index change by using a series of small refractive index steps.

Fig. 11A illustrates a planar silicon waveguide film.

Figs. 11B-G show a profile of the propagating mode of a silicon waveguide film with a thickness of 0.4 micron, 0.3 micron, 0.2 micron, 0.1 micron, 0.05 micron, and 0.01 micron, respectively.

Fig. 12 shows the mode size of the propagating mode of a silicon waveguide as a function of the waveguide core thickness.

Fig. 13 is a side view of a vertically down-tapered basic mode transformation module according to the present invention.

Fig. 14 is a result of a computer simulation of light propagation in the module of Fig. 13.

Fig. 15A-C illustrates exemplary fabrication steps for the module of Fig. 13.

Fig. 16 is a top view of a horizontally/laterally down-tapered basic mode transformation module according to the present invention.

Fig. 17 is a result of a computer simulation of light propagation in the module of Fig. 16.

Fig. 18A-D illustrates exemplary fabrication steps for the module of Fig. 16.

Fig. 19 is a top view of a horizontally/laterally up-tapered basic mode transformation module according to the present invention.

Fig. 20 is a result of a computer simulation of light propagation in the module of Fig. 19.

Fig 21A-E illustrates exemplary fabrication steps for the module of Fig. 19.

Fig. 22A-B are, respectively, a top and a side view of a vertically down-tapered, horizontally/laterally up-tapered basic mode transformation module according to the present invention.

Fig. 23 is a result of a computer simulation of light propagation in the module of Fig. 22.

Fig 24A-F illustrates exemplary fabrication steps for the module of Fig. 22.

Fig. 25 is a perspective view of a glass/polymer waveguide module with a step refractive index in the vertical and horizontal/lateral direction according to the present invention.

Fig. 26 is a result of a computer simulation of light propagation in the module of Fig. 25.

Fig. 27A-E illustrates exemplary fabrication steps for the module of Fig. 25.

Fig 28 is a perspective view of a glass/polymer waveguide module with a step refractive index in the horizontal/lateral direction and a graded refractive index in the vertical direction according to the present invention.

Fig. 29 is a result of a computer simulation of light propagation in the module of Fig. 28.

Fig. 30A-D illustrates exemplary fabrication steps for the module of Fig. 28.

Fig. 31 is a perspective view of a glass/polymer waveguide module with a graded refractive index in both the horizontal/lateral direction and the vertical direction according to the present invention.

Fig. 32 is a result of a computer simulation of light propagation in the module of Fig. 31.

Fig. 33A-B illustrates exemplary fabrication steps for the module of Fig. 31.

Fig. 34A-B are, respectively, a side view and a top view of a super mode transformation coupler with a vertically down-tapered, horizontally/laterally up-tapered high-index waveguide core embedded in a glass/polymer waveguide with a graded refractive index in the vertical direction and a step refractive index in the horizontal/lateral direction according to the present invention.

Fig. 35 is a result of a computer simulation of light propagation in the super mode transformation coupler of Fig. 34.

Fig. 36A-N illustrate exemplary fabrication steps for the super mode transformation coupler of Fig. 34.

Fig. 37A-B are, respectively, a side view and a top view of a super mode transformation coupler with a vertically down-tapered, horizontally/laterally down-tapered high-index waveguide core embedded in a glass/polymer waveguide with a graded refractive index in both the horizontal/lateral and the vertical direction according to the present invention.

Fig. 38 is a result of a computer simulation of light propagation in the super mode transformation coupler of Fig. 37.

Fig. 39A-N illustrate exemplary fabrication steps for the super mode transformation coupler of Fig. 37.

Fig. 40A is a side view of a super mode transformation coupler with a vertically down-tapered high-index waveguide core embedded in a glass/polymer waveguide with a non-symmetric graded refractive index in the vertical direction and a step refractive index in the horizontal/lateral direction according to the present invention.

Fig. 40B is a top view of the super mode transformation coupler of Fig. 40A, in which the high-index waveguide core is horizontally up-tapered.

Fig. 40C is an alternative top view of the super mode transformation coupler of Fig. 40A, in which the high-index waveguide core is horizontally down-tapered.

Fig. 41 is a result of a computer simulation of light propagation in the super mode transformation coupler of Fig. 40A.

Fig. 42A-N illustrate exemplary fabrication steps for the super mode transformation couplers of Fig. 40.

Fig. 43 is a result of a computer simulation of light propagation in a variation of the super mode transformation coupler of Fig. 40A.

Fig. 44A-C illustrate exemplary fabrication steps for a variation of the super mode transformation coupler of Fig. 40A.

Fig. 45A-C illustrate exemplary fabrication steps for mounting an optical fiber and a semiconductor optical device coupled by a super mode transformation coupler according to the present invention.

Fig. 46 illustrates a device in which a number of semiconductor optical devices are coupled to a number of optical fibers using super mode transformation couplers according to the present invention.

Fig. 47 is a schematic illustration of a photonic breadboard on which various integrated photonic chips are mounted and interconnected via coupler modules according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

<u>CONTENTS OF DETAILED DESCRIPTION</u>

(4) Exemplary device 4:a vertical sharp-down-taper and lateral gradual-up-taper (VSDT×LGUT) ICMT device

(5) Exemplary device 5: a lateral -step-refractive-index and vertical -step-refractive-index (LSRIN×VSRIN) ICMT device

(6) Exemplary device 6:

(A) a composite-lateral-step-refractive-index and vertical-graded-refractive index (LSRIN×VGRIN) ICMT device

(B) a composite-lateral-graded-refractive-index and vertical-graded-refractive index (LGRIN×VGRIN) ICMT device

(7) Exemplary device 7: a vertical-sharp-down-taper-and-lateral-gradual-up-taper-cascaded-with-a-vertical-graded-refractive-index-and-lateral-step-refractive-index (VSDT×LGUT + VGRIN×LSRIN) ICMT device

(8) Exemplary device 8: a vertical-sharp-down-taper-and-lateral-sharp-down-taper-embedded-in-a-symmetric-vertical-graded-refractive-index-and-lateral-graded-refractive-index (VSDT×LSDT + VGRIN×LGRIN) ICMT device

(9) Exemplary device 9: a vertical-sharp-down-taper-cascaded-with-a-nonsymmetric-vertical-graded-refractive-index- (VSDT + NSVGRIN) ICMT device

(10) Variations of exemplary devices and integration of ICMT with v-grooves for fiber alignments platform for photonic chips

IV. Applications

DESCRIPTION OF THE SPECIFIC EXEMPLARY EMBODIMENTS

I. General background and Terminology:

Described herein are various exemplary processes and embodiments of the integrated composite mode transformer (ICMT) structures of the present invention. The structures can, for example, be used to provide efficient beam transformation between a photonic waveguide device and one or more optical fibers, wherein the transformation can correct for astigmatic beam sizes in the waveguides of the photonic devices. The ICMT structures can further be placed on a platform for self-alignment with the photonic device and one or more optical fibers.

To be consistent throughout the present specification and for clear understanding of the present invention, the following background and terminological definitions are hereby provided for terms used therein:

(a) Refractive index, optical wavelength, law of reflection, Snell's law of refraction, critical angle

As is well known, light is an electromagnetic wave oscillating at very high frequency. When light travels in an electrically nonconductive medium such as glass, its speed will be reduced as compared to traveling in a vacuum and the ratio of the phase velocity of light in a vacuum (c) to that in a medium (v) is the **refractive index** n of the medium, $n=\frac{c}{v}$. Due to the fact that the frequency of the wave will not change as light travels from vacuum into a medium, the optical wavelength in a medium, λ, is thus reduced to $\lambda = \lambda_0/n$, where λ_0 is the wavelength in a vacuum.

Light can be regarded as a ray traveling in a straight line within a medium of the same refractive index if the size of the medium (such as a lens) is much greater than the wavelength. At an optical interface **710** of two different refractive indices n_i and n_t, a light ray will be reflected back into the first medium **720** (n_i) and also refracted/transmitted into the second medium **730** (n_t) as shown in Fig. 7. Law of reflection tells us that the angle of incidence (θ_i) equals the angle of reflection (θ_r) and **Snell's law of refraction** says that the refraction angle (θ_t) is related to the incidence angle (θ_i) through the equation

$$n_i \sin \theta_i = n_t \sin \theta_t.$$

However, if $n_i > n_t$, as θ_i increases to a particular value called the **critical angle**, θ_c will reach 90°, and afterwards, the incident light ray will be totally reflected **740**. Thus, as shown in Fig. 8, light guiding in a step refractive index optical waveguide or fiber can be explained by successive total internal reflections **810**.

(b) Optical waveguide, planar waveguide, channel waveguide

From the above, we see that an **optical waveguide** is made up of a material with a high refractive index, surrounded by materials with a lower refractive index. The optical energy that is guided lies primarily within the layer with high refractive index. The layer with high refractive index is called the waveguide core while the surrounding layers with low refractive indices are called the waveguide cladding. If the waveguide is in the form of a two-dimensional layered structure, it is known to those skilled in the art as **a planar waveguide** for which optical energy will be confined to guide along a plane. If the waveguide

core is in the form of a cylindrical or rectangular or other bar type shape, it is known to those skilled in the art as a **channel waveguide**. While the present application is primarily directed towards channel waveguides, planar waveguides are often used to demonstrate the basic idea of the principles involved because of their simplicity.

(c) Graded refractive index and related waveguide structures, parabolic distribution, periodic focusing

As shown in Fig. 9, in a **graded refractive index (GRIN) optical waveguide** or fiber **910**, the waveguiding material has a refractive index that decreases continuously from the central axis. In this case, light rays travel through the waveguide or fiber in a fashion as shown in Fig. 9. Such a GRIN waveguide relies on refraction and not reflection, except possibly at the cladding layer.

A **parabolic refractive index distribution** will cause the light rays to bend towards the axis and to get **refocused periodically.** As shown in Fig. 10, the behavior can be simply explained by modeling the continuous change as a series of small step changes **1010**. Note that at each step or interface, the bending of the ray follows the law of refraction. As the ray travels from the axis **1020** to the low refractive index region, at each step or interface, it will bend further towards the horizontal direction until the incident angle exceeds the critical angle in which case, the ray will be totally internally reflected **1030**. Now the ray is traveling from low to high refractive index medium and hence, the law of refraction tells us that at each boundary or interface, the ray will bend towards the axis until it crosses the axis. Afterward, it will repeat the cycle. Note that, in addition to guiding light, the GRIN waveguide also functions as a lens to focus or expand/collimate a beam of light if the waveguide is cut into the right length.

(d) Wave behavior and critical wave-behavior dimension (CWBD) for waveguide taper

When the size of the guiding region is no longer much larger than the wavelength but rather smaller than the wavelength, the ray concept can no longer give an accurate picture of how light propagates, and one must resort to **wave theory** to better describe light propagation. As an example, consider a semiconductor taper embedded in a glass medium. There exists a critical wave-behavior dimension (CWBD) for the waveguide taper of CWBD = $\lambda_0 / \left(4\sqrt{n_c^2 - n_{cl}^2}\right)$ (where λ_0 is the wavelength in vacuum, n_c is the refractive index of the tapering waveguide core and n_{cl} is the refractive index of the waveguide cladding), below which light will penetrate substantially into the cladding medium while being guided. Fig. 11b to 11f show the electric field profile of the propagating mode for a

silicon waveguide **1110 (Fig 11a)** with a thickness equal to 0.4 μm, 0.3 μm, 0.2 μm, 0.1 μm, 0.05 μm, and 0.01 μm, respectively. In Fig. 11, the x-axis indicates space position across the waveguide in μm, the y-axis indicates normalized electric field of the lowest transverse electric ("TE") mode. The wavelength of light is 1.5 μm, the refractive index of the cladding **1120** is assumed to be 1.5 and the refractive index of the silicon waveguide core **1110** is assumed to be 3.5. Fig. 12 plots the mode size (given by the full-width at half maximum of the mode intensity) as a function of the waveguide core thickness t. From Fig. 12, as the Si waveguide thickness decreases, the mode size first decreases and then starts to become larger at approximately $t = 1.5/\left(4\sqrt{3.5^2 - 1.5^2}\right) \approx 0.1 \mu m$.

<u>(e) Propagating refractive index of waveguide, waveguide end facet reflectance, sharp-tip tapered waveguide, sharp taper and gradual taper</u>

In an optical waveguide, it is useful to define the **propagating refractive index** of the waveguide as $n_g = n_c \sin(\theta_i)$. This propagating refractive index takes a value between the refractive index of the core n_c and the refractive index of the cladding n_{cl}. As the waveguide gets thinner, θ_i approaches the critical angle, and n_g approaches the refractive index of the cladding n_{cl}. In fact, most of the optical energy will reside in the cladding when *t* is very small. If this waveguide (thinner than the critical wave-behavior dimension CWBD) is abruptly terminated at an end facet, beyond which is filled by the cladding material, the reflectance (percentage of reflected optical power with respective to the incident optical power) for a guided wave hitting the end facet is given approximately by the **end facet reflectance** of $R = \left(\frac{n_g - n_{cl}}{n_g + n_{cl}}\right)^2$. Hence, such end-facet reflectance can be reduced to zero provided n_g approaches n_{cl}, which will be the case if the waveguide is very thin (i.e. all is transmitted).

A waveguide with a gradually decreasing or increasing thickness along the direction of propagation is called a taper waveguide. A taper waveguide can in some way be seen as composed of many waveguide sections with decreasing or increasing thickness. From the above discussion, we see that a waveguide taper that tapers down to a near-zero thickness will first reduces the mode size and when the mode hits a region with a thickness smaller than the critical thickness, the mode size will starts to be enlarged. Furthermore, since the thickness of the waveguide approaches zero at the taper end, we can expect the optical power reflection at the taper end isto be negligible. Thus, a waveguide taper that tapers down to near

zero thickness (a sharp-tip tapered waveguide) can be used to enlarge the mode size of a guided wave and also reduce the end facet reflection to a negligible value at the same time. Such a sharp-tip tapered waveguide will be referred to as "sharp taper" as opposed to "gradual taper"; a gradual taper will not taper down to reach the CWBD or reach a sharp tip. A gradual taper, for example, will slowly reduce the mode size and is typically used as a mode reducer. Furthermore, a gradual down taper will have reflection at the end face and will typically use anti-reflection techniques to reduce the end facet reflection.

The foregoing description serves as a general background providing a context within which embodiments of the present invention will be described below and are not meant to restrict any of the embodiment of the present invention.

II. General Introduction

When a submicron semiconductor channel waveguide is to be connected to a single mode optical fiber with a typical dimension of about 10 μm, one critical need is the expansion or enlargement of the mode size from the semiconductor channel waveguide to match that of the optical fiber, or the reverse process.

According to the embodiments of present invention, several different mode transformation and coupling structures can be cost effectively fabricated in either a single structure format or a composite structure format forming various mode transformation modules.

As discussed above, the integrated composite mode transformer (ICMT) structures include at least three types of basic mode transformation structures, namely:

(I). The sharp-taper structure (ST) includes a sharp tapering in either the vertical direction (VST) or the lateral direction (LST). These structures may be referred to below simply as ST, VST, and LST, respectively, with the high-refractive-index-contrast assumed. The sharp taper can further be distinguished as down or up depending on the direction of assumed mode propagation. For the purpose of nomencleture convenience only, the mode propagating direction below is taken to be from the photonic chip to the optical fiber. Those skilled in the art will readily be able to generalize it to other mode propagating configurations.

(II). The gradual-taper structure (GT), includes gradual tapering in either the vertical direction (VGT) or the lateral direction (LGT). These structures may be referred

to below simply as GT, VGT, and LGT respectively. The gradual taper can further be distinguished as down or up and the propagating direction issue is as described in (I).

(III). The micro graded refractive index structure (μ-GRIN) includes a graded refractive index distribution in either the vertical (μ-VGRIN) or lateral (μ-LGRIN) directions. These structures may be referred to below simply as GRIN, VGRIN, or LGRIN. The GRIN structure can further be distinguished as symmetric or non-symmetric depending on whether the graded index has a profile symmetric or asymmetric with respect to the optical axis of propagation for the input wave.

Further, the sharp taper (ST) and the gradual taper (GT) may be in the form of high refractive index contrast structures and will be referred to as HRC-ST and HRC-GT, respectively. The high refractive index contrast enables much shorter tapering lengths to be used while maintaining large transformation of mode sizes.

A brief description of some of these basic module types are provided below.

(I). HRC-ST (High-Refractive-Index-Contrast, Sharp Taper Structure)

In this structure type, a high-refractive-index waveguide layer with vertical or lateral tapering to a sharp tip provides the mode size transformation. For the case of vertical tapering, the high-index waveguide layer is fabricated on top of a lower cladding layer. The upper and side cladding material may be either identical to or different from the lower cladding; hence the cladding index can be either symmetric or asymmetric. One novel feature of embodiments of this structure is the high contrast of the refractive index of the down taper waveguide core relative to the refractive index of the cladding, which confines propagating light to a very small mode size. For example, for the case where the material of the waveguide core is Si; the refractive index can be as high as about 3.5. The cladding material can be glass of various compositions that can have a range of refractive index values from about 1.45 to about 2.5. The sharp point of the taper must reach a dimension smaller than the critical wave-behavior dimension of CWBD = $\lambda_0 / \left(4\sqrt{n_c^2 - n_{cl}^2}\right)$ introduced above. In that case, transformation of the mode size from as small as λ/15, (submicron for λ = 1.5 μm) to a few λ (a few microns for λ = 1.5 μm) can be typically achieved.

(II). HRC-GT (High-Refractive-Index-Contrast, Gradual Taper Structure)

In this structure type, a gradual taper provides the mode size transformation in either the lateral or the vertical direction. The mode size transformation is due to the fact that gradual mode size will follow the waveguide size if the waveguide changes size gradually. One aspect of the embodiments of this structure is the high contrast of the refractive index of

the taper waveguide core relative to the refractive index of the cladding, which allows it to achieve large changes in the mode size within a short propagation distance.

(III). μ-GRIN (Micro-Graded-Refractive-Index Structure)

In this structure type, a graded refractive index layer with either a vertical or lateral refractive index gradiant provides the mode size transformation. For the case of a vertical graded refractive index structure, a stepwise refractive index distribution (e.g., the core has a first constant index, and the cladding has a second constant index, lower than the first) or a graded refractive index distribution (index varies throughout the waveguide, in one of the embodiments, being highest near the center) is present in the vertical direction. One feature of the embodiments of this structure is the smallness of the structure, for which the GRIN structure is less than about 50 μm. This thickness is small relative to the diameter of the optical fiber.

The above three basic beam-transforming structure types together with other waveguide structures, are combined in various composite ways in the vertical and lateral directions, to form different basic beam-transforming modules. The composite structures allows a basic module to transform the beam size in either the vertical or lateral direction, or both the vertical and lateral directions.

Furthermore, two or more basic modules can be cascaded spatially to form a combined module. The combined module can be used to either increase the degree of mode transformation over that of a basic module, or to have one basic module perform the vertical mode size transformation and another basic module perform the lateral mode size transformation.

Described below are specfic embodiments of various mode transforming devices based on the integrated composite mode transformer (ICMT) structures of the present invention. The various basic modules as well as the combined modules will be described. In the sequence of presentation below, this includes:

(1) A downward VST or vertical sharp down taper (VSDT) to enlarge the vertical mode size of an optical beam from a photonic chip to an optical fiber (e.g., Figs. 13-15).

(2) A downward LST or lateral sharp down taper (LSDT) to enlarge the lateral mode size of an optical beam from a photonic chip to an optical fiber (e.g., Figs. 16-18).

(3) An upward LGT or lateral gradual up taper (LGUT) to enlarge the latral mode size of an optical beam from a photonic chip to an optical fiber (e.g., Figs. 19-21).

(4) A composite VSDT and LGUT structure forming a (VSDT×LGUT) module to enlarge the mode size vertically and laterally for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 22-24).

(5) A step-refactive-index (SRIN) waveguide module that provides simple wave propagation without mode size transformation. This SRIN module is used as a basic module to combine with other modules (e.g., Figs. 25-27). In the case illustrated in Figures 25-27, a vertical step index waveguide (VSRIN) and a lateral step index waveguide (LSRIN) structures are combined to provide simple mode waveguiding in both the vertical and the lateral directions.

(6) A composite vertical graded refractive index (VGRIN) and LSRIN structure forming a (VGRIN×LSRIN) module to enlarge the vertical mode size for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 28-30).

(7) A composite vertical graded refractive index (VGRIN) and laterial graded refractive index (LGRIN) structure forming a (VGRIN×LGRIN) module to enlarge the mode size vertically and laterally for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 31-33).

(8) A combined module including a cascaded (VSDT×LGUT) module and (VGRIN×LSRIN) module, namely a (VSDT×LGUT) + (VGRIN×LSRIN) combined module, to increase the enlargement of the mode size vertically and laterally for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 34-36).

(9) A combined module made up of a cascade of (VSDT×LSDT) module and (VGRIN×LGRIN) module, namely a (VSDT×LSDT) + (VGRIN×LGRIN) combined module, to increase the enlargement of the mode size vertically and laterally for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 37-39).

(10) A combined module made up of either a cascade of (VSDT×LGUT) module and (VGRIN×LSRIN) module with asymmetric GRIN structure, namely a (VSDT×LGUT) + (VGRIN×LSRIN) combined asymmetric GRIN module, or a cascade of (VSDT×LSDT) module and a (VGRIN×LGRIN) module with asymmetric GRIN structure, namely a (VSDT×LSDT) + (VGRIN×LGRIN) combined asymmetric GRIN module, to increase the enlargement of the mode size vertically and laterally for an optical beam from a photonic chip to an optical fiber (e.g., Figs. 40-43).

(11) A waveguide bonding process useful for the fabrication of the vertical sharp taper structures (e.g., Fig 44)

(12) The integration of the ICMT structures with a V-groove structure for fiber on one side and an alignment platform for photonic chip on the other side. Such an integrated structure allows self-alignment of the ICMT with a photonic chip and an optical fiber (e.g., Fig. 45-46).

While the exemplary devices (1) – (12) typically refer to transformation of an optical beam between a photonic chip and optical fibers, it is not meant to limit the applications, embodiments, or scopes of the exemplary devices. It should be clear to those skilled in the art that these exemplary devices can be more generally used to transform optical beams from any type of small core waveguide to any type of large core waveguide or vice versa.

III. EXEMPLARY DEVICES AND EMBODIMENTS

Beam transforming devices based on ICMT according to embodiments of the present invention are described in detail below.

The devices will be described with respect to transmission of a single light beam with wavelength λ. It should be understood that the terms light beam, optical beam, laser beam, etc., are used interchangeably. Moreover, while descriptions of the devices refer to a single light beam, there may be more than one light beam propagating in the device, the light beams may be made up of light with many wavelengths, the light beam may be continuous-wave light or pulsed light, and the light beam may have various beam sizes. Thus the nature of the light beam is used only for illustrative purposes and is not meant to limit the scope of the invention.

Unless otherwise stated, the exemplary dimensions below will be specified with respect to an exemplary optical wavelength of 1.5 μm. Those skilled in the art will know that the exemplary dimensions will scale proportionally to the wavelength used which can range from ultra-violet (e.g., on the order of 0.1μm)to far infrared (e.g., on the order of 10μm).

The various device embodiments described herein are useful for transforming the mode size of an input beam having a dimension on the order of from about 0.2μm or even less to a beam dimension on the order of about 10μm to 50μm or more, and vice versa, with appropriate changes to the various device parameters disclosed. Thus one skilled in the art should understand that the various device embodiment parameters (e.g., length and width

dimensions) disclosed herein are exemplary and may be varied according to the desired application.

(1) EXEMPLARY DEVICE 1: A HIGH-REFRACTIVE-INDEX-CONTRAST VERTICAL SHARP-DOWN-TAPER (HRC-VSDT) ICMT DEVICE

FIG. 13 illustrates a first general embodiment of an ICMT device **1300** employing a vertical down-tapering beam enlarger with high refractive-index contrast between the enlarger core region and its surrounding cladding region. The device performs as a one dimensional beam-size enlarging element in the vertical direction for a propagating optical beam and can, for example, enlarge an optical beam from a semiconductor waveguide with a beam size as small as $\lambda/7.5$ (or 0.2μm for $\lambda = 1.5$ μm) to a large optical beam such as one with a beam size more than five times larger. The device is not limited to use as a beam enlarger but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used in conjunction with another ICMT module such as a graded refractive index waveguide module (described below) to further enlarge and collimate the beam for direct coupling into an optical fiber and vice versa. It should be understood that these exemplary applications of device **1300** are intended to illustrate the uses for device **1300** and are not intended to limit the applications of other embodiments of device **1300**. The device can be referred to as a "high-refractive-index-contrast -vertical-sharp-down-taper (HRC-VSDT) ICMT".

HRC-VSDT ICMT **1300** preferably includes a tapering-down waveguiding core region occupied by Waveguide Core WC **1345**. Waveguide Core WC **1345** is surrounded by Upper Waveguide Cladding UWCL **1350** above and Lower Waveguide Cladding LWCL **1310** below. The Waveguide Core WC **1345** preferably includes a small-beam input/output port SB-PT **1346**, a straight waveguiding core region SWC **1347**, a tapering-down waveguiding core region TDWC **1348**, a straight radiation core region SRC **1351**, and a large-beam output/input port LB-PT **1349**. The straight waveguiding core region SWC **1347** has a length l_{SWC} and a thickness t_{SWC}. The tapering down waveguiding core region TDWC **1348** has a length l_{TDWC}, a thickness t_{TDWCSB} at the small-beam input/output side and a thickness t_{TDWCLB} at the large-beam input/output side. The straight radiation core region SRC **1351** has a length l_{SRC} and a thickness t_{SRC}. The total length of the waveguide core is given by $l_{WC} = l_{SWC} + l_{TDWC} + l_{SRC}$. The thickness of the lower waveguide cladding LWCL **1310** is t_{LWCL}. The thickness of the upper waveguide cladding UWCL **1350** at the

small-beam input/output side is t_{UWCLSB} and at the large-beam input-output side is t_{UWCLLB}. The length of the upper cladding l_{UWCL} and the length of the lower cladding l_{LWCL} are about equal to the total length of the waveguide core l_{WC}. The refractive index of the Waveguide Core WC **1345** is n_{WC}. The refractive index of the Upper Waveguide Cladding UWCL **1350** is n_{UWCL}. The refractive index of the Lower Waveguide Cladding LWCL **1310** is n_{LWCL}. Lower waveguide cladding LWCL **1310** is formed on a substrate **1315** as will be described in more detail below. The length of the straight waveguide core l_{SWC} and the straight radiation core l_{SRC} are typically not very critical to the operation of the device and can be zero in some applications (i.e., with these sections absent).

For choice of refractive index, there are three options for operation for the ICMT device **1300**, namely the small-refractive-index-contrast option, the medium-refractive-index-contrast option and the large-refractive-index-contrast option. For the small-refractive-index contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1345** and that of the Waveguide Cladding **1350** or **1310**, i.e. n_{WC}/n_{UWCL} or n_{WC}/n_{LWCL}, is assumed to be larger than 1.0 but smaller than about 1.3. That is $1.3 \geq n_{WC}/n_{UWCL} > 1.0$ or $1.3 \geq n_{WC}/n_{LWCL} > 1.0$. For the medium-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1345** and that of the Waveguide Cladding **1350** or **1310**, i.e. n_{WC}/n_{UWCL} or n_{WC}/n_{LWCL}, is assumed to be larger than about 1.3 but smaller than about 1.5. That is $1.5 \geq n_{WC}/n_{UWCL} \geq 1.3$ or $1.5 \geq n_{WC}/n_{LWCL} \geq 1.3$. For the large-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1345** and that of the Waveguide Cladding **1350** or **1310**, i.e. n_{WC}/n_{UWCL} or n_{WC}/n_{LWCL}, is assumed to be larger than about 1.5. That is $n_{WC}/n_{UWCL} \geq 1.5$ or $n_{WC}/n_{LWCL} \geq 1.5$. A short tapering length can be achieved if the relative refrective index contrast is high – in the region of either the medium-refractive-index contrast or the large-refractive-index contrast. The medium and large refractive index contrast will be referred to as the high-refractive index case.

In an exemplary device, the input/output port SB-PT **1346** is configured to receive/transmit a light beam **1341** typically having wavelength λ with a beam diameter d_{SB}, and the output/input port LB-PT **1349** is configured to transmit/receive a light beam **1342** typically having wavelength λ with a beam diameter d_{LB}.

(i) An Exemplary Device for High-Refractive-Index-Contrast Case

In an exemplary embodiment of device **1300** with high refractive-index contrast, the Waveguide Core WC **1345** is made up of silicon (Si) with a refractive index of

$n_{WC} = 3.5$, the Upper Waveguide Cladding **1350** is made up of silica-titania (SiO_2-TiO_2) material mixture with a mixture composition to achieve a refractive index of $n_{UWCL} = 1.7$ or alternatively Si_3N_4 with a refractive index of about 1.7 can be used. The Lower Waveguide Cladding **1310** is made up of silicon dioxide (SiO_2) with a refractive index of $n_{LWCL} = 1.5$. The thicknesses of the waveguide core are $t_{SWC} = 0.3$ μm, $t_{TDWCSB} = 0.3$ μm, and $t_{TDWCLB} = t_{SRC} = 0$, by "0" it is meant that $t_{TDWCLB} = t_{SRC} << \lambda$. The thicknesses of the waveguide claddings are $t_{UWCLSB} = 5.0$ μm, $t_{UWCLLB} = 5.3$ μm, and $t_{LWCL} = 0.6$ μm. The lengths of the waveguide core are $l_{SWC} = 10$ μm, $l_{TDWC} = 30$ μm, $l_{SRC} = 10$ μm, and $l_{WC} = 50$ μm. The lengths of the waveguide claddings are $l_{UWCL} = l_{LWCL} = l_{WC} = 50$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly. It should also be appreciated by one skilled in the art that other materials for the core and cladding of the various exemplary embodiments may be used.

(ii) General Operation of the Device.

FIG. 14 shows the results of a computer simulation of the spatial distribution of the electric field strength for light input at $\lambda = 1.5$ μm after propagating into waveguide **1347**, using the above exemplary parameters. The mode size at the input end was approximately 0.3 μm. After propagating for about 35 μm, it begins to expand at the point where the waveguide thickness (at 5 μm distance from the tip) is tapered down to about 0.05 microns, which is near the tip of the tapering down region. The mode then radiates at an angle from that point to a larger mode size. The mode size reaches a size of about 5 μm at 10 μm away from the tip of the taper. The compact mode transfer device thus expands the mode from about 0.3 to about 5 μm over a distance of about 50 μm. This is a much smaller distance compared with mode expansion distances provided by other prior art devices . Thus such ICMT devices according to the present invention provide a clear advantage for coupling fibers to a photonic chip relative to prior art devices.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating a HRC-VSDT-ICMT such as device **1300** will now be described with reference to FIG. 15A-C. This procedure is given for the purpose of illustration and not limitation as other similar procedures can be used to achieve

the same fabrication results, and other materials systems or device structures can be utilized to fabricate devices with the same functional capabilities.

The HRC-VSDT-ICMT type structure is fabricated according to an embodiment by starting with a Silicon-On-Insulator (SOI) wafer. For a SOI wafer, a high refractive index silicon (Si) layer **1305** having a thickness of t_{SWC} is already made or bonded on top of a low refractive index layer of SiO_2 **1310** with a thickness of t_{LWCL}. The SiO_2 layer **1310** is typically either deposited on a Si substrate **1315** or thermally oxidized on the Si substrate or thermally oxidized in the Si substrate after an oxygen ion implantation process. A fabrication procedure according to one embodiment is now described below.

A photoresist layer **1320** is deposited (e.g. spin-coated) on the silicon layer **1305**, as shown in FIG. 15A. A gray-scale mask **1325** is used as a mask to expose the photoresist **1320** under UV light **1330**. The gray-scale mask pattern is designed so that it provides a graduated exposure level with an exposure dosage that varies from a small value to a large value that will somewhat result in a linear photoresist taper after exposure and development across a length of approximately 30 μm. The photoresist is then developed. The shape of the photoresist after exposure and development has a vertical down tapered shape that corresponds to the variation in the exposure dosage, as shown by photoresist pattern **1335** in FIG. 15B.

A dry plasma etching procedure **1340** with selectivity of 1:0.3:~0 between photoresist and Si and SiO_2 is used to etch down the Si layer vertically. Such a process is accomplished using a reactive ion etching system, or an inductively coupled plasma system, or another equivalent dry plasma system. The exemplary processing gases are $SF_6/O_2/Cl_2$, as F-reactants and/or their neutrals etch Si, whereas O_2 etch photoresist and S-Cl reactants and/or their neutrals inhibit the etching of SiO_2. Exemplary process parameters using a reactive ion etching system are: a mixture of 30sccm:20sccm:20sccm of SF_6:O_2:Cl_2, with an RF power of 350W, and a process pressure of 25 mTorr. This etching process transfers the down tapered pattern of the photoresist to the high-refractive-index Si layer and forms the vertically tapered down Si section **1345**. It should be noted that the ease of this transfer process is dependent on the thickness t_{SWC} of the top waveguiding Si layer. Typically the starting thickness for a tapered down Si waveguide is in the range of 0.2 to 0.5 μm. Considering that the photoresist layer has a typical thickness of about 1.0 μm and that the etching process typically etches Si at a rate that is not drastically different from that for the photoresist, such a direct pattern transfer can be achieved. As the etching process can be

made to etch SiO_2 at a lower rate, the interface between the top Si layer **1305** and the lower cladding SiO_2 **1310** can be used as a natural stop during the dry etching process. It should be understood that the above process parameters are presented for purposes of illustrating a useful embodiment of the fabrication method and are not intended as a limitation on the device. For example, a variety of dry etching parameters can be used depending on the photoresist type and the quality of the SOI wafer. As is known to those skilled in the art, the end result of a dry etched structure can be achieved via various combinations of the etching parameters.

To make the glass upper cladding layer **1350**, flame hydrolysis deposition, chemical vapor deposition, sputtering, Ion-Assisted-Deposition or sol-gel spin coating of dielectric material, can generally be employed to deposit the upper cladding layer **1350**, shown in Fig. 15C. The TiO_2-SiO_2 material required can, in particular, be achieved using a sol-gel mixture of TiO_2 and SiO_2 precursors as is well known to those skilled in the art. The surrounding cladding, including the bottom, top and side cladding medium, can all have various refractive indices and also a spatial variation or distribution of the refractive index value (as will be discussed below), and the actual value that can be selected for this purpose can cover a wide range, for instance 1.4 to 2.5.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1300** and are not intended to limit other embodiments of any exemplary device, or the device **1300**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the various embodiments of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device **1300** can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(2) EXEMPLARY DEVICE 2: A HIGH-REFRACTIVE-INDEX-CONTRAST- LATERAL SHARP-DOWN-TAPER (HRC-LSDT) ICMT DEVICE

Fig. 16 illustrates a second general embodiment of an ICMT device **1400** employing a lateral down-tapering beam enlarger with high refractive-index contrast between the enlarger core region and its surrounding cladding region. The device performs as a one dimensional beam-size enlarging element in the lateral direction for a propagating optical beam and can, for example, enlarge an optical beam from a semiconductor waveguide with a beam size as small as $\lambda/7.5$ (or $0.2\mu m$ for $\lambda = 1.5\ \mu m$) to a large optical beam such as one with a beam size close to that of an optical fiber. The device is not limited to use as a beam enlarger but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used in conjunction with another ICMT module such as a graded-refractive-index waveguide module to further enlarge and collimate the beam for direct coupling into an optical fiber. It should be understood that these exemplary applications of device **1400** are intended to illustrate the uses for device **1400** and are not intended to limit the application of other embodiments of device **1400** to these examples. The device can be referred to as a "high-refractive-index-contrast-lateral-sharp-down-taper (HRC-LSDT) ICMT".

The present HRC-LSDT ICMT preferably includes a tapering-down waveguiding core region occupied by Waveguide Core WC **1450**, Waveguide Core WC **1450** is surrounded on both sides by Waveguide Cladding WCL **1460**. Waveguide Core **1450** preferably includes a small-beam input/output port SB-PT **1451**, a straight waveguiding core region SWC **1452**, a tapering-down waveguiding core region TDWC **1453**, a straight radiation core region SRC **1454**, and a large-beam input/output port LB-PT **1455**. The

straight waveguiding core region SWC **1452** has a length l_{SWC} and a width of w_{SWC}. The tapering down waveguiding core region TDWC **1453** has a length of l_{TDWC}, a width of w_{TDWCSB} at the small-beam input/output side, and a width w_{TDWCLB} at the large-beam input/output side. The straight radiation core region SRC **1454** has a length of l_{SRC} and a width of w_{SRC}. The total length of the waveguide core is given by $l_{WC} = l_{SWC} + l_{TDWC} + l_{SRC}$. The width of the waveguide cladding WCL **1460** on both sides of the waveguide core WC **1450** is w_{WCLSB} at the small beam input/output side, and is w_{WCLLB} at the large beam side. The length of the waveguide cladding WCL **1460** l_{WCL} is about equal to the total length of the waveguide core l_{WC}. The refractive index of the Waveguide Core WC **1450** is n_{WC}. The refractive index of the Waveguide Cladding WCL **1460** is n_{WCL}. The length of the straight waveguide core l_{SWC} and the straight radiation core l_{SRC} are typically not very critical to the operation of the device and can be zero in some applications (i.e. with these sections absent).

For choice of refractive index, there are three options for the operation of the ICMT device **1400**, namely the small-refractive-index-contrast option, the medium-refractive-index-contrast option and the large-refractive-index-contrast option. For the small-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1450** and that of the Waveguide Cladding **1460** i.e. n_{WC}/n_{WCL}, is assumed to be larger than 1.0 but smaller than 1.3. That is, $1.3 \geq n_{WC}/n_{WCL} \geq 1.0$. For the medium-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1450** and that of the Waveguide Cladding **1460** i.e. n_{WC}/n_{WCL}, is assumed to be larger than 1.3 but smaller than 1.5. That is, $1.5 \geq n_{WC}/n_{WCL} \geq 1.3$. For the large-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1450** and that of the Waveguide Cladding **1460** i.e. n_{WC}/n_{WCL}, is assumed to be larger than 1.5. That is, $n_{WC}/n_{WCL} \geq 1.5$. A short tapering length can be achieved if the relative refrective index contrast is HIGH – in the region of either the medium-refractive-index contrast or the large-refractive-index contrast. The medium and large refractive index contrast will be referred to as the high-refractive index case.

In an exemplary device, the input/output port SB-PT **1451** is configured to receive/transmit a light beam **1461** typically having wavelength λ with a beam width w_{SB}, and the input/output port LB-PT **1455** is configured to receive/transmit a light beam **1465** typically having wavelength λ with a beam width w_{LB}.

(i) An Exemplary Device for High-Refractive-Index-Contrast Case

In an exemplary embodiment of device **1400** in the high-refractive-index-contrast operation region, the Waveguide Core WC **1450** is made up of silicon (Si) with a refractive index of $n_{WC} = 3.5$, the Waveguide Cladding WCL **1460** is made up of silica-titania (SiO_2-TiO_2) material mixture with a mixture composition to achieve a refractive index of $n_{UWCL} = 1.7$ or alternatively Si_3N_4 with a refractive index of about 1.7 can be used. The widths of the waveguide core are $w_{SWC} = 0.3$ μm, $w_{TDWCSB} = 0.3$ μm, and $w_{TDWCLB} = w_{SRC} = 0$ μm. The widths of the waveguide claddings are $w_{WCLSB} = 4.85$ μm and $w_{WCLLB} = 5.0$ μm. The lengths of the waveguide core regions are $l_{SWC} = 0$ μm, $l_{TDWC} = 30$ μm, $l_{SRC} = 26$ μm, and $l_{WC} = 56$ μm. The length of the waveguide cladding is $l_{WCL} = 56$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 17 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at $\lambda = 1.5$ μm after propagating into waveguide **1452**. The mode size at the input end was 0.3 μm. After propagating for 25 μm, it begins to expand at the point where the waveguide thickness (at 5 μm from the tip) is tapered down to 0.05 microns, which is near the tip of the tapering down region. The mode then radiates at an angle from that point to a larger mode size. The mode size reaches a size of about 10 μm at 10 μm away from the tip of the taper.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating HRC-LSDT-ICMT device **1400** will now be described with reference to FIG. 18A-D. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The HRC-LSDT ICMT can be fabricated by starting with a Silicon-On-Insulator (SOI) wafer. For a SOI wafer, a high refractive index silicon (Si) layer **1410** having a thickness of t_1 is already made or bonded on top of a low refractive index layer of SiO_2 **1415** with a thickness of t_2. The SiO_2 layer **1415** is typically either deposited on a Si substrate **1420** or thermally oxidized on the Si substrate or thermally oxidized in the Si substrate after

an oxygen ion implantation process. A fabrication procedure according to one embodiment is described below:

A UV or e-beam resist layer **1405** is first spin-coated on the Si layer **1410**, as shown in Fig. 18B. A mask **1425** with a laterally tapered down/narrow mask pattern **1430** as shown in Fig. 18A is used as a mask to expose the photoresist **1405** under UV light or e-beam **1435**. The photoresist is then developed. The shape of the photoresist after exposure and development has a lateral down-tapered shape as shown by photoresist pattern **1440** in Fig. 18B and Fig. 18C.

A dry plasma etching procedure **1445** that selectively etches Si but not the photoresist **1440** or the SiO_2 **1415** is used. Such a process can be accomplished using a reactive ion etching system, or an inductively coupled plasma system, or any dry plasma system. The exemplary processing gases are SF_6/Cl_2, as F-reactants and/or their neutrals etch Si, and S-Cl reactants and/or their neutrals inhibit the etching of SiO_2. Exemplary process parameters using a reactive ion etching system are: a mixture of approximately 30sccm:20sccm of SF_6:Cl_2, with an RF power of 200W, and a process pressure of about 25 mTorr. This etching process transfers the laterally down tapered pattern of the photoresist **1440** to the high-refractive-index Si layer and forms the laterally tapered down Si section **1450**. It should be noted that this transfer process is performed with the starting thickness for the Si waveguide layer in the range of 0.2 to 0.5 μm, and the photoresist layer has a typical thickness of about 1.0 μm. As the etching process can be made to etch SiO_2 at a lower rate, the interface between the top Si layer **1410** and the lower cladding SiO_2 **1415** can be used as a natural stop during the dry etching process. A top view of the result of the process is shown in Fig. 18D. It should be understood that the above process parameters are presented for purposes of illustrating a useful embodiment of the fabrication method and are not intended to limit other embodiments of the method. For example, a variety of dry etching parameters can be used depending on the photoresist type and the quality of the SOI wafer. As is known to those skilled in the art, the end result of a dry etched structure can be achieved via various combinations of the etching parameters. It should, also be noted that due to the limitation in the smallest feature size of UV based photolithography, e-beam lithography might be necessary or at least it might be required to form the tip part of the taper.

To make the glass cladding **1460**, flame hydrolysis deposition, chemical vapor deposition, sputtering, Ion-Assisted-Deposition, or sol-gel spin coating of dielectric material, is employed to deposit the cladding regions **1460** shown in Fig. 16. The TiO_2-SiO_2 material

required can, in particular, be achieved using a sol-gel mixture of TiO_2 and SiO_2 precursors as is well known to those skilled in the art. Note that the surrounding cladding, including the bottom, top and side cladding medium, can all have various fixed or spatially varying or distributed refractive indices and also a spatial variation or distribution of the refractive index value (as described below), and the actual value that can be selected for this purpose can cover a wide range of 1.4 to 2.5.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1400** and are not intended to limit other embodiments of any exemplary device, or the device **1400**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device **1400** can be fabricated on adifferent substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(3) EXEMPLARY DEVICE 3: A HIGH-REFRACTIVE-INDEX-CONTRAST-LATERAL GRADUAL-UP-TAPER (HRC-LGUT) ICMT DEVICE

Fig. 19 illustrates a third general embodiment of an ICMT device **1500** employing lateral tapering up beam enlarger with high refractive index contrast between the enlarger core region and its surrounding cladding region. The device performs as a one dimensional beam-size enlarging element in the lateral direction for a propagating optical beam and can for example enlarge an optical beam from a semiconductor waveguide with a beam size as small as $\lambda/7.5$ (or 0.2μm for $\lambda = 1.5$ μm) to a large optical beam such as one with a beam size close to that of an optical fiber. The device is not limited to use as a beam enlarger but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used in conjunction with another ICMT module such as a step-index waveguide module as will be described below to further collimate the beam for direct coupling into an optical fiber. It should be understood that these exemplary applications of device **1500** are intended to illustrate the uses for device **1500** and are not intended to limit the application of other embodiments of device **1500**. The device can be referred to as a "high-refractive-index-contrast-lateral-gradual-up-taper (HRC-LGUT) ICMT", and the tapering up is in the lateral direction.

The present HRC-LGUT ICMT preferably includes a tapering-up waveguiding core region occupied by Waveguide Core WC **1550**. Waveguide Core WC **1550** is surrounded on both sides by Waveguide Cladding WCL **1560**. Waveguide Core **1550** preferably includes a small-beam input/output port SB-PT **1551**, a straight waveguiding core region SWC **1552**, a tapering-up waveguiding core region TUWC **1553**, a straight radiation core region SRC **1554**, and a large-beam input/output port LB-PT **1555**. The straight waveguiding core region SWC **1552** has a length l_{SWC} and a width of w_{SWC}. The tapering up waveguiding core region TUWC **1553** has a length of l_{TUWC}, a width of w_{TUWCSB} at the small-beam input/output side, and a width w_{TUWCLB} at the large-beam input/output side. The straight radiation core region SRC **1554** has a length of l_{SRC} and a width of w_{SRC}. The total length of the waveguide core is given by $l_{WC} = l_{SWC} + l_{TUWC} + l_{SRC}$. The width of the waveguide cladding WCL **1560** on both sides of the waveguide core WC **1550** is w_{WCLSB} at the small beam input/output side, and is w_{WCLLB} at the large beam side. The length of the waveguide cladding WCL **1560** l_{WCL} is about equal to the total length of the waveguide core l_{WC}. The refractive index of the Waveguide Core WC **1550** is n_{WC}. The refractive index of the Waveguide Cladding WCL **1560** is n_{WCL}. The length of the straight waveguide core l_{SWC} and

the straight radiation core l_{SRC} are typically not very critical to the operation of the device and can be zero in some applications (i.e. with these sections absent).

There are three options for the refractive index contrast of the ICMT device **1500**, namely the small-refractive-index-contrast option, the medium-refractive-index-contrast option and the large-refractive-index-contrast option. For the small-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1550** and that of the Waveguide Cladding **1560** i.e. n_{WC}/n_{WCL}, is assumed to be larger than 1.0 but smaller than about 1.3. That is $1.3 \geq n_{WC}/n_{WCL} \geq 1.0$. For the medium-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1550** and that of the Waveguide Cladding **1560** i.e. n_{WC}/n_{WCL}, is assumed to be larger than about 1.3 but smaller than about 1.5. That is $1.5 \geq n_{WC}/n_{WCL} \geq 1.3$. For the large-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1550** and that of the Waveguide Cladding **1560** i.e. n_{WC}/n_{WCL}, is assumed to be larger than about 1.5. That is $n_{WC}/n_{WCL} \geq 1.5$. A short tapering length can be achieved if the relative refrective index contrast is HIGH – in the region of either the medium-refractive-index contrast or the large-refractive-index contrast. In an exemplary device, the input/output port SB-PT **1551** is configured to receive/transmit a light beam **1561** typically having wavelength λ with a beam width w_{SB}, and the input/output port LB-PT **1555** is configured to receive/transmit a light beam **1565** typically having wavelength λ with a beam width w_{LB}. The medium and large refractive index contrast will be referred to as the high-refractive index case.

(i) An Exemplary Device for High-Refractive-Index-Contrast Case

In an exemplary embodiment of device **1500** with high-refractive-index-contrast, the Waveguide Core WC **1550** is made up of silicon (Si) with a refractive index of $n_{WC} = 3.5$, the Waveguide Cladding WCL **1560** is made up of silica-titania (SiO_2-TiO_2) material mixture with a mixture composition to achieve a refractive index of nUWCL = 1.7 or alternatively Si_3N_4 with a refractive index of about 1.7 can be used. Twith a refractive index of nWCL = 1.7. The widths of the waveguide core are $w_{SWC} = 0.3$ μm, $w_{TUWCSB} = 0.3$ μm, and $w_{TUWCLB} = w_{SRC} = 10$ μm. The widths of the waveguide claddings are $w_{WCLSB} = 6.85$ μm and $w_{WCLLB} = 2$ μm. The lengths of the waveguide core regions are $l_{SWC} = 10$ μm, $l_{TUWC} = 100$ μm, $l_{SRC} = 10$ μm, and $l_{WC} = 120$ μm. The length of the waveguide cladding is $l_{WCL} = 120$ μm. It should be appreciated by one skilled in the art that all parameter values used in this

and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 20 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at λ = 1.5 μm after propagating into waveguide **1552**. The mode size at the input end was 0.3 μm. After propagating for 10 μm, it begins to expand at the point where the waveguide core tapers up. The mode then enlarges following the up-tapering waveguide core section to a larger mode size. The mode size reaches a size of about 10 μm at the end of the up-taper.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating an LGUT-ICMT device **1500** will now be described with reference to Fig. 21A-E. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

It should be noted that the fabrication steps here are very similar to those described for the laterally tapered down case. In fact, the present structure is even easier to fabricate because e-beam lithography is not required and hence the cost is even lower. The HRC-LGUT ICMT type structure can be fabricated by starting with a Silicon-On-Insulator (SOI) wafer that can be fabricated via a commercial process known to those skilled in the art. For a SOI wafer, a high refractive index silicon (Si) layer **1510** having a thickness of t_1 is already made or bonded on top of a low refractive index layer of SiO_2 **1515** with a thickness of t_2, as shown in Fig. 21A. The SiO_2 layer **1515** is typically either deposited on a Si substrate **1520** or thermally oxidized on the Si substrate or thermally oxidized in the Si substrate after an oxygen ion implantation process. The fabrication procedure according to one embodiment is now described below.

A photoresist layer **1505** is first spin-coated on the Si layer **1510**, as shown in Fig. 21A. A mask **1525** with a laterally tapered up mask pattern **1530**, shown in Fig. 21B, is used as a mask to expose the photoresist **1505** under UV light **1535**. The photoresist is then developed. The shape of the photoresist after exposure and development has a lateral up tapered shape as shown by photoresist pattern **1540** in Fig. 21D.

A dry plasma etching procedure **1545** that selectively etches Si but not the photoresist **1540** or the SiO_2 **1515** can be used, as shown in Fig. 21C. Such an etch process is accomplished using a reactive ion etching system, or an inductively coupled plasma system, or any dry plasma system. The exemplary processing gases are SF_6/Cl_2, as F-reactants and/or their neutrals etch Si, and S-Cl reactants and/or their neutrals inhibit the etching of SiO_2. Exemplary process parameters using a reactive ion etching system are: a mixture of 30sccm:20sccm of SF_6:Cl_2, with an RF power of 200W, and a process pressure of 25 mTorr. This etching process transfers the laterally up tapered pattern of the photoresist **1540** to the high-refractive-index Si layer and forms the laterally up-tapered Si section **1550**. It should be noted that this transfer process is possible because the starting thickness of the Si waveguide layer is in the range of 0.2 to 0.5 μm, and the photoresist layer has a typical thickness of about 1.0 μm. As the etching process can be made to etch SiO_2 at a lower rate, the interface between the top Si layer **1510** and the lower cladding SiO_2 **1515** can be used as a natural stop during the dry etching process. It should be understood that the above process parameters are presented for purposes of illustrating a useful embodiment of the fabrication method and are not intended to limit other embodiments of the method. For example, a variety of dry etching parameters can be used depending on the photoresist type and the quality of the SOI wafer. As is known to those skilled in the art, the end result of a dry etched structure can be achieved via various combinations of the etching parameters.

To make the glass cladding **1560**, flame hydrolysis deposition, chemical vapor deposition, sputtering, Ion-Assisted-Deposition, or sol-gel spin coating of dielectric material, can generally be employed to deposit the cladding regions **1560** shown in Fig. 19. The TiO_2-SiO_2 material required can, in particular, be achieved using a sol-gel mixture of TiO_2 and SiO_2 precursors as is well known to those skilled in the art. Note that the surrounding cladding, including the bottom, top and side cladding medium, can all have various refractive indices and also a spatial variation or distribution of the refractive index value (as described below), and the actual value that can be selected for this purpose can cover a wide range, for instance 1.4 to 2.5.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1500** and are not intended to limit other embodiments of any exemplary device, or the device **1500**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device 1500 can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(4) EXEMPLARY DEVICE 4: A VERTICAL SHARP-DOWN-TAPER AND LATERAL GRADUAL-UP-TAPER (HRC-VSDT×LGUT) ICMT DEVICE

Fig. 22A-B illustrates a fourth general embodiment of an ICMT device **1600** including a lateral gradual up-tapered and vertical sharp down-tapered beam transformer with high refractive index contrast between the enlarger core region and its surrounding cladding region. The device can perform as a two dimensional beam-size enlarging element in both the lateral and the vertical directions for a propagating optical beam and can, for example, enlarge an optical beam from a semiconductor waveguide with a beam size as small as $\lambda/7.5$ (or 0.2μm for $\lambda = 1.5$ μm) to a large optical beam such as one with a beam size more than five times larger. The device is not limited to use as a beam enlarger but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the

device can be used other ICMT modules such as a lateral step-index waveguide module and a vertical graded index waveguide module as will be discussed below to further collimate the beam for direct coupling into an optical fiber. It should be understood that these exemplary applications of device **1600** are intended to illustrate the uses for device **1600** and are not intended to limit the applications of other embodiments of device **1600**. The device can be referred to as a "high-refractive-index-contrast-vertical sharp-down-taper and lateral gradual-up-taper ICMT" (HRC-VSDT×LGUT ICMT).

The present HRC-VSDT×LGUT ICMT preferably includes a laterally up-tapered and vertically down-tapered waveguiding core region occupied by Waveguide Core WC **1650**. When viewed from the top, Waveguide Core WC **1650** is surrounded on both sides by Side Waveguide Cladding SWCL **1670**. Waveguide Core **1650** preferably includes a lateral small-beam input/output port LSB-PT **1671**, a laterally straight waveguiding core region LSWC **1672**, a laterally tapering-up waveguiding core region LTUWC **1673**, a laterally straight radiation core region LSRC **1674**, and a lateral large-beam input/output port LLB-PT **1675**. The laterally straight waveguiding core region LSWC **1672** has a length l_{LSWC} and a width of w_{LSWC}. The laterally tapering up waveguiding core region LTUWC **1673** has a length of l_{LTUWC}, a lateral width of $w_{LTUWCSB}$ at the small-beam input/output side, and a width $w_{LTUWCLB}$ at the large-beam input/output side. The laterally straight radiation core region LSRC **1674** has a length of l_{LSRC} and a width of w_{LSRC}. The total length of the waveguide core when viewed from the top is given by $l_{WC} = l_{LSWC} + l_{LTUWC} + l_{LSRC}$. The width of the side waveguide cladding SWCL **1670** on both sides of the waveguide core WC **1650** is w_{SWCLSB} at the small beam input/output side, and is w_{SWCLLB} at the large beam side. The length of the side waveguide cladding SWCL **1670** l_{SWCL} is about equal to the total length of the waveguide core l_{WC}. The length of the straight waveguide core l_{LSWC} and the straight radiation core l_{LSRC}. are typically not very critical to the operation of the device and can be zero in some applications (i.e., with these sections absent).

When viewed from the side, Waveguide Core WC **1650** is surrounded at the bottom by Lower Waveguide Cladding LWCL **1615**, and at the top by Upper Waveguide Cladding UWCL **1690**. Waveguide Core **1650** preferably includes a vertical small-beam input/output port VSB-PT **1691**, a vertically straight waveguiding core region VSWC **1692**, a vertically tapering-down waveguiding core region VTDWC **1693**, a vertically straight radiation core region VSRC **1694**, and a vertical large-beam input/output port VLB-PT **1695**. The vertically straight waveguiding core region VSWC **1692** has a length l_{VSWC} and a

thickness of t_{VSWC}. The vertically tapering down waveguiding core region VTDWC **1693** has a length of l_{VTDWC}, a vertical thickness of $t_{VTDWCSB}$ at the small-beam input/output side, and a vertical thickness of $t_{VTDWCLB}$ at the large-beam input/output side. The vertically straight radiation core region VSRC **1694** has a length of l_{VSRC} and a thickness of t_{VSRC}. The total length of the waveguide core when viewed from the side is given by $l_{WC} = l_{VSWC} + l_{VTDWC} + l_{VSRC}$. The thickness of the lower waveguide cladding LWCL **1615** is t_{LWCL}. The thickness of the upper waveguide cladding UWCL **1690** at the small-beam input/output side is t_{UWCLSB} and at the large-beam input-output side is t_{UWCLLB}. The length of the upper cladding l_{UWCL} and the length of the lower cladding l_{LWCL} are about equal to the total length of the waveguide core l_{WC}. The length of the straight waveguide core l_{LSWC} and the straight radiation core l_{LSRC}. are typically not very critical to the operation of the device and can be zero in some applications (i.e., with these sections absent).

The refractive index of the Waveguide Core WC **1650** is n_{WC}. The refractive index of the Side Waveguide Cladding SWCL **1670** is n_{SWCL}. The refractive index of the Lower Waveguide Cladding LWCL **1615** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **1690** is n_{UWCL}.

There are three options for the refractive index of the ICMT device **1600**, namely the small-refractive-index-contrast option, the medium-refractive-index-contrast option and the large-refractive-index-contrast option. For the small-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1650** and that of the Waveguide Claddings **1615/1690/1670** i.e. n_{WC}/n_{LWCL}, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, is assumed to be larger than 1.0 but smaller than about 1.3. That is $1.3 \geq n_{WC}/n_{LWCL}$, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, ≥ 1.0. For the medium-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1650** and that of the Claddings **1615/1690/1670** i.e. n_{WC}/n_{LWCL}, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, is assumed to be larger than 1.3 but smaller than about 1.5. That is $1.5 \geq n_{WC}/n_{LWCL}$, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, ≥ 1.3. For the large-refractive-index-contrast option, the refractive index ratio between the refractive index of the Waveguide Core **1650** and that of the Claddings **1615/1690/1670** i.e. n_{WC}/n_{LWCL}, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, is assumed to be larger than about 1.5. That is n_{WC}/n_{LWCL}, n_{WC}/n_{UWCL}, n_{WC}/n_{SWCL}, ≥ 1.5. A short tapering length can be achieved if the relative refrective index contrast is high – in the region of either the medium-refractive-index contrast or the large-refractive-index contrast. The medium and large refractive index contrast will be referred to as the high-refractive index case.

In an exemplary device, the input/output port LSB-PT/VSB-PT **1671/1691** is configured to receive/transmit a light beam **1678/1698** typically having wavelength λ with a lateral beam width w_{LSB}, and a vertical beam width w_{VSB}. The input/output port LLB-PT/VLB-PT **1675/1695** is configured to receive/transmit a light beam **1679/1699** typically having wavelength λ with a lateral beam width of w_{LLB}, and a vertical beam width of w_{VLB}.

(i) An Exemplary Device

In an exemplary embodiment of device **1600**, the Waveguide Core WC **1650** is made up of silicon (Si) with a refractive index of $n_{WC} = 3.5$, the Lower Waveguide Cladding LWCL **1615** is made up of silica (SiO_2) with a refractive index of $n_{LWCL} = 1.5$, and the Upper and Side Waveguide Claddings UWCL/SWCL are made of silica-titania (SiO_2-TiO_2) material mixture with a mixture composition to achieve a refractive index of $n_{UWCL} = 1.7$ or alternatively Si_3N_4 with a refractive index of about 1.7 can be used.

When viewed from the top, the lateral widths of the waveguide core are $w_{LSWC} = 0.3$ μm, $w_{LTUWCSB} = 0.3$ μm, and $w_{LTUWCLB} = w_{LSRC} = 10$ μm. The widths of the side waveguide claddings are $w_{SWCLSB} = 4.85$ μm and $w_{SWCLLB} = 0$ μm. The lengths of the waveguide core regions are $l_{LSWC} = 10$ μm, $l_{LTUWC} = 100$ μm, $l_{LSRC} = 10$ μm, and $l_{WC} = 120$ μm. The length of the side waveguide cladding is $l_{SWCL} = 120$ μm.

When viewed from the side, the vertical thicknesses of the waveguide core are $t_{VSWC} = 0.3$ μm, $t_{VTDWCSB} = 0.3$ μm, and $t_{VTDWCLB} = t_{VSRC} = 0$. The thicknesses of the upper and lower waveguide claddings are $t_{UWCLSB} = 9.7$ μm, $t_{UWCLLB} = 10$ μm, and $t_{LWCL} = 0.6$ μm. The lengths of the waveguide core regions are $l_{VSWC} = 80$ μm, $l_{VTDWC} = 30$ μm, $l_{VSRC} = 0$ μm, and $l_{WC} = 110$ μm. The lengths of the upper and lower waveguide claddings are $l_{UWCL} = l_{LWCL} = l_{WC} = 120$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

Fig 23 shows the result of a computer simulation of the spatial distribution of the electric field strength in the vertical and lateral directions for the light input at $\lambda = 1.5$ μm after propagating into waveguide **1672/1692**. The mode size at the input end was 0.3 μm in both the vertical and lateral directions.

When viewed from the side, the light beam begins to expand at the point where the waveguide thickness (at 5 μm distance from the tip) is tapered down to 0.05 microns, which is near the tip of the tapering down region. The mode then radiate at an angle from that point to a larger mode size. The mode size reaches a size of about 5 μm at 10 μm away from the tip of the taper.

When viewed from the top, the light beam begins to expand at the point where the waveguide core tapers up laterally. The mode then enlarges following the lateral up-tapering waveguide core section **1673** to a larger mode size. The mode size reaches a size of about 10 μm at the end of the up-taper.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating the HRC-VSDT×LGUT ICMT device **1600** will now be described with reference to FIG. 24A-F. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The HRC-VSDT×LGUT ICMT is fabricated by starting with a Silicon-On-Insulator (SOI) wafer. For a SOI wafer, a high refractive index silicon (Si) layer **1610** having a thickness of t_1 is already made or bonded on top of a low refractive index layer of SiO_2 **1615** with a thickness of t_2, as illustrated in Fig. 24A. The SiO_2 layer **1615** is typically either deposited on a Si substrate **1620** before wafer bonding or thermally oxidized on the Si substrate before wafer bonding or thermally oxidized in the Si substrate after an oxygen ion implantation process. The fabrication procedure according to one embodiment is now described below:

A photoresist layer **1605** is first spin-coated on the Si layer **1610**, as shown in Fig. 24A. A mask **1625** with a pattern **1630** as shown in Fig. 24B is used to expose the photoresist **1605** under UV light **1635**. The mask pattern **1630** is gray scaled in the longitudinal direction and laterally tapered up in the lateral direction. The gray-scale mask pattern is designed so that it gives a graduated exposure level with exposure dosage that varies from a small value to a large value across a length of 30 μm. The photoresist is then developed. The shape of the photoresist after exposure and development is a vertical down tapered shape that corresponds to the variation in the exposure dosage and a laterally tapered up shape as shown by photoresist pattern **1640** in Fig. 24C and Fig. 24D.

A dry plasma etching procedure **1645** with selectivity of 1:0.3:~0 between photoresist and Si and SiO_2 is used to etch down the Si layer vertically. Such a process is accomplished using a reactive ion etching system, or an inductively coupled plasma system, or any dry plasma system. The exemplary processing gases are $SF_6/O_2/Cl_2$, as F-reactants and/or their neutrals etch Si, whereas O_2 etches photoresist and S-Cl reactants and/or their neutrals inhibit the etching of SiO_2. Exemplary process parameters using a reactive ion etching system are: a mixture of 30sccm:20sccm:20sccm of $SF_6:O_2:Cl_2$, with an RF power of 350W, and a process pressure of 25 mTorr. This etching process transfers the laterally up tapered and vertically down tapered pattern of the photoresist **1640** to the high-refractive-index Si layer and forms the laterally tapered up and vertically tapered down Si section **1650**. The resulting structure is shown in Fig. 24E and 24F. It should be noted that the easiness of this transfer process is dependent on the thickness t_1 of the top waveguiding Si layer. Typically the starting thickness for such a Si waveguide should be in the range of 0.2 to 0.5 μm. Considering that the photoresist layer has a typical thickness of about 1.0 μm and that the etching process typically etches Si at a rate that is not drastically different from that for the photoresist, such a direct pattern transfer can be achieved. As the etching process can be made to etch SiO_2 at a much slower rate, the interface between the top Si layer **1610** and the lower cladding SiO_2 **1615** can be used as a natural stop during the dry etching process. It should be understood that the above process parameters are presented for purposes of illustrating a useful embodiment of the fabrication method and are not intended to limit other embodiments of the method. For example, a variety of dry etching parameters can be used depending on the photoresist type and the quality of the SOI wafer. As is known to those skilled in the art, the end result of a dry etched structure can be achieved via various combinations of the etching parameters.

To make the glass cladding, flame hydrolysis deposition, chemical vapor deposition, sputtering, Ion-Assisted-Deposition, or sol-gel spin coating of dielectric material, can generally be employed to deposit the top and side cladding regions **1690/1670** shown in Fig. 22A-B. The TiO_2-SiO_2 material required can, in particular, be achieved using a sol-gel mixture of TiO_2 and SiO_2 precursors as is well known to those skilled in the art. Note that the surrounding cladding, including the bottom, top and side cladding medium, can all have various refractive indices and also a spatial variation or distribution of the refractive index value (described below), and the actual value that can be selected for this purpose can cover a wide range, e.g., 1.4 to 2.5.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1600** and are not intended to limit other embodiments of any exemplary device, or the device **1600**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device 1600 can be fabricated on adifferent substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

<u>(5) EXEMPLARY DEVICE 5: A LATERAL -STEP-REFRACTIVE-INDEX AND VERTICAL -STEP-REFRACTIVE-INDEX (LSRIN×VSRIN) ICMT DEVICE</u>

Fig. 25 illustrates a fifth general embodiment of an ICMT device **1700** including a vertical and lateral step refractive index distribution to form a step index channel waveguide with refractive index difference between the core region and its surrounding cladding region. The device can perform as a two dimensional beam-size collimating element

in both the lateral and the vertical directions for a propagating optical beam and can, for example, confine an optical beam that has already been expanded or enlarged from a small semiconductor waveguide using devices such as any of exemplary devices 1-4. The device is not limited to use as a beam collimator but can also function as a waveguide to direct a light beam to a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **1700** are intended to illustrate the uses for device **1700** and are not intended to limit the applications of other embodiments of device **1700**. The device can be referred to as a "low-refractive-index-contrast-vertical-step-refractive-index and lateral-step-refractive-index (LRC-LSRIN×VSRIN) ICMT".

The present LRC-LSRIN×VSRIN ICMT preferably includes a waveguiding core region occupied by Waveguide Core WC **1730**. Waveguide Core WC **1730** is surrounded at the bottom by Lower Waveguide Cladding LWCL **1710**, on the top by Upper Waveguide Cladding UWCL **1745** and on both sides by Side Waveguide Cladding SWCL **1720**. Waveguide Core **1730** preferably includes a front beam input/output port FB-PT **1731**, a straight waveguiding core region SWC **1730**, and a back beam input/output port BB-PT **1732**. The straight waveguiding core region SWC **1730** has a length l_{SWC}, a width of w_{SWC} and a thickness of t_{SWC}. Lower Waveguide Cladding LWCL **1710** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. Upper Waveguide Cladding UWCL **1745** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The two side waveguide claddings SWCL **1720** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **1710/1745/1720**, l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the waveguide core l_{WC}. The refractive index of the Waveguide Core WC **1730** is n_{WC}. The refractive index of the Lower Waveguide Cladding LWCL **1710** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **1710** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **1710** is n_{SWCL}.

In an exemplary device, the front beam input/output port FB-PT **1731** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber, and the back beam input/output port LB-PT **1732** is also configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the Waveguide Core WC **1730** is made up of lead-titania-silica with a refractive index of $n_{WC} = 1.71$, or Si_3N_4 with a refractive index of about 1.7. The Lower Waveguide Cladding LWCL **1710** is made up of silica with a refractive index of $n_{LWCL} = 1.5$. The Upper Waveguide Cladding UWCL is made up of silica-titania with a refractive index of $n_{UWCL} = 1.7$, or Si_3N_4 with a refractive index of about 1.7. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index of $n_{SWCL} = 1.7$, or Si_3N_4 with a refractive index of about 1.7. The size of the waveguide core is $l_{WC} = 50$ µm, $w_{WC} = 10$ µm and $t_{WC} = 10$ µm. The size of the lower waveguide cladding is $l_{LWCL} = 50$ µm, $w_{LWCL} = 20$ µm and $t_{LWCL} = 1$ µm. The size of the upper waveguide cladding is $l_{UWCL} = 50$ µm, $w_{UWCL} = 20$ µm and $t_{UWCL} = 1$ µm. The size of the two side waveguide claddings is $l_{SWCL} = 50$ µm, $w_{SWCL} = 5$ µm and $t_{SWCL} = 10$ µm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 26 shows the result of a computer simulation of the spatial distribution of the electric field strength for the light input at $\lambda = 1.5$ µm after propagating into waveguide **1730**. The mode size at the input end is 10 µm. The waveguide confines the mode and guides its propagation to the other port. The mode size remains at about 10 µm at the other end of the waveguide.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating the LRC-LSRIN×VSRIN ICMT device **1700** will be described with reference to Fig. 27A-E. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The LRC-LSRIN×VSRIN ICMT can be fabricated by starting with a Silica-On-Silicon (SOS) wafer that can be fabricated via a commercial process known to those skilled in the art, as shown in Fig. 27A. For a SOS wafer, a low refractive index layer of SiO_2 **1710** with a thickness of t_{LWCL} is already made on the Si substrate (not shown). The SiO_2 layer **1710** is typically either deposited on a Si substrate or thermally oxidized on the Si substrate. There are at least two possible ways to fabricate the LRC-LSRIN×VSRIN ICMT.

Method 1: As shown in Fig. 27A, a dielectric or glass waveguiding film **1705** is deposited on the SiO_2 layer **1710**, which acts as a lower waveguide cladding. Depending on the dielectric material, an appropriate film deposition method can be used including evaporation, sputtering, Ion-Assisted-Deposition, chemical vapor deposition, flame hydrolysis, and spin or dip coating. As is well known to those skilled in the art, a common way to make a lateral step refractive index distribution is to dry etch a stripe **1706** in the deposited film. This can be easily achieved by photolithography. A photoresist layer **1702** can be deposited and UV-exposed through a conventional stripe mask. After photoresist development, a photoresist stripe pattern **1703** is generated, as shown in Fig. 27B. Dry etching can then be used to transfer the photoresist stripe pattern to the dielectric or glass waveguide film **1705** to form a stripe pattern **1706**, shown in Fig. 27C. While air can be used as the top and side cladding, generally speaking, a surrounding cladding material is preferred and such a cladding **1715**, which acts both as the upper waveguide cladding and the side waveguide cladding, can always be deposited, as shown in Fig. 27C.

Method 2: Another approach to make a step refractive index distribution in the lateral direction is to first deposit a photosensitive waveguide film **1720** on the SiO_2 **1710**, as shown in Fig. 27D. In the case of silica-based glass, typically, Ge or Pb can be incorporated to make the glass film photosensitive. The incorporation of Ge or Pb for making a glass film photosensitive are described in a copending U.S. patent application number 09/884, 691 having the same inventors herein, entitled: "Method for Forming a Refractive-Index-Patterned Film for Use in Optical Device Manufacturing," the disclosure of which is hereby

incorporated by reference herein in its entirety. After the deposition of such a film **1720**, UV photo-imprinting **1725** through a conventional photomask **1735** can be used to define a refractive index increased stripe **1730**. If an upper cladding is preferred, a film **1745** with a refractive index lower than that of the photoimprinted stripe can then be deposited, as shown in Fig. 27E. Alternatively, such a film can even be deposited before the UV photoimprinting as long as this upper cladding film does not substantially absorb the UV light. An obvious advantage of the photoimprinting approach is that the fabrication of a buried channel waveguide is significantly simplified as it does not involve etching, and hence the fabrication cost is also significantly lowered.

Either of the two methods produces a buried channel waveguide that has a step refractive index distribution in both the vertical and the horizontal/lateral direction.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1700** and are not intended to limit other embodiments of any exemplary device, or the device **1700**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device **1700** can be fabricated on adifferent substrate other than a silicon substrate. In particular, it can be

fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(6) EXEMPLARY DEVICE 6

(A) A COMPOSITE-LATERAL-STEP-REFRACTIVE-INDEX AND VERTICAL-GRADED-REFRACTIVE INDEX (LSRIN×VGRIN) ICMT DEVICE

Fig. 28 illustrates a sixth general embodiment of an ICMT device **1800** including a vertically graded and laterally step refractive index distribution to form a channel waveguide. The device **1800** can perform as a two dimensional beam-size collimating element in both the lateral and the vertical directions for a propagating optical beam and can, for example, confine and collimate an optical beam that has already been expanded or enlarged from a small semiconductor waveguide using a device such as any of exemplary devices 1-4. The device is not limited to use as a beam collimator but can also function as a waveguide to direct a light beam to a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **1800** are intended to illustrate the uses for device **1800** and are not intended to limit the applications of other embodiments of device **1800**. The device can be referred to as a "composite-lateral-step-refractive-index and vertical-graded-refractive index (LSRIN×VGRIN) ICMT".

LSRIN×VGRIN ICMT **1800** preferably includes a waveguiding core region occupied by Waveguide Core WC **1835**. Waveguide Core WC **1835** is surrounded at the bottom by Lower Waveguide Cladding LWCL **1810**, on the top by Upper Waveguide Cladding UWCL **1840** and on both sides by Side Waveguide Cladding SWCL **1825**. Waveguide Core **1835** preferably includes a front beam input/output port FB-PT **1831**, a straight waveguiding core region SWC **1835**, and a back beam input/output port BB-PT **1832**. The straight waveguiding core region SWC **1835** has a length l_{SWC}, a width of w_{SWC} and a thickness of t_{SWC}. The Lower Waveguide Cladding LWCL **1810** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. The Upper Waveguide Cladding UWCL **1840** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The two side waveguide claddings SWCL **1825** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **1810/1840/1825**, l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the waveguide core l_{WC}. The refractive index of the Waveguide

Core WC **1835** is not a constant. It is graded in the vertical direction and varies from the center of the core to the outer border of the core; the variation is represented by $n_{WC}(y)$ with y being the vertical coordinate. In the horizontal or lateral direction, the refractive index has a step profile. In other words, for a particular vertical coordinate y_0, the refractive index is a constant $n_{WC}(y_0)$ within the core region and drops to the refractive index value of the side cladding $n_{SWCL}(y_0)$ at the two side borders. The refractive index of the Lower Waveguide Cladding LWCL **1810** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **1840** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **1825** is $n_{SWCL}(y)$, which means it is y-coordinate dependent.

In an exemplary device, the front beam input/output port FB-PT **1831** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that is already fully enlarged in the lateral direction and partially enlarged to an intermediate size in the vertical direction by a high-refractive-contrast tapered waveguide, and the back beam input/output port LB-PT **1832** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the Waveguide Core WC **1835** is made up of lead-titania-silica with a refractive index distribution that approximates a parabolic distribution as given in Table I below.

Table I Refractive index distribution

y coordinate (μm)	Refractive index of WC	Refractive index of SWCL
-5.0 to –4.6	1.610	1.600
-4.6 to –4.2	1.624	1.614
-4.2 to –3.8	1.636	1.626
-3.8 to –3.4	1.648	1.638
-3.4 to –3.0	1.658	1.648
-3.0 to –2.6	1.668	1.658
-2.6 to –2.2	1.676	1.666
-2.2 to –1.8	1.683	1.673
-1.8 to –1.4	1.688	1.678
-1.4 to –1.0	1.693	1.683
-1.0 to –0.6	1.696	1.686
-0.6 to –0.2	1.699	1.689
-0.2 to 0.2	1.700	1.690
0.2 to 0.6	1.699	1.689

0.6 to 1.0	1.696	1.686
1.0 to 1.4	1.693	1.683
1.4 to 1.8	1.688	1.678
1.8 to 2.2	1.683	1.673
2.2 to 2.6	1.676	1.666
2.6 to 3.0	1.668	1.658
3.0 to 3.4	1.658	1.648
3.4 to 3.8	1.648	1.638
3.8 to 4.2	1.636	1.626
4.2 to 4.6	1.624	1.614
4.6 to 5.0	1.610	1.600

The Lower Waveguide Cladding LWCL **1810** is made up of silica with a refractive index of $n_{LWCL} = 1.5$. The Upper Waveguide Cladding UWCL is made up of silica-titania with a refractive index of $n_{UWCL} = 1.6$. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index of distribution given by Table I. The size of the waveguide core is $l_{WC} = 50$ μm, $w_{WC} = 10$ μm and $t_{WC} = 10$ μm. The size of the lower waveguide cladding is $l_{LWCL} = 50$ μm, $w_{LWCL} = 30$ μm and $t_{LWCL} = 10$ μm. The size of the upper waveguide cladding is $l_{UWCL} = 50$ μm, $w_{UWCL} = 30$ μm and $t_{UWCL} = 10$ μm. The size of the two side waveguide claddings is $l_{SWCL} = 50$ μm, $w_{SWCL} = 10$ μm and $t_{SWCL} = 10$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 29 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at $\lambda = 1.5$ μm after propagating into waveguide **1835**. The mode size at the input end is 10 μm in both the lateral and vertical directions. In the lateral direction, the waveguide confines the mode and guides its propagation to the other port. In the vertical direction, in addition to the guiding of the light beam, the waveguide also functions as a lens in the sense that the beam size is changed periodically.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating LSRIN×VGRIN ICMT device **1800** will now be described with reference to Fig. 30A-D. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the

same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The LSRIN×VGRIN ICMT can be fabricated by starting with a Silica-On-Silicon (SOS) wafer that can be fabricated via a commercial process known to those skilled in the art. For a SOS wafer, as shown in Fig. 30A, a low refractive index layer of SiO_2 **1810** with a thickness of t_{LWCL} is already made on the Si substrateb (not shown). There are at least two ways to fabricate the LSRIN×VGRIN ICMT structure and these are now described by fabrication methods 1-2 below:

Method 1: As shown in Fig 30A, a graded index distribution in the vertical direction can be achieved by depositing multiple sufficiently thin layers of different material compositions **1805** on a lower cladding layer **1810**. In such a case, a continuous distribution of the refractive index can be approximated by a series of small effective refractive index steps with each thin layer having a different refractive index value. Depending on the property of the dielectric material, an appropriate film deposition method can be used. These methods include evaporation, flame hydrolysis, sputtering, Ion-Assisted-Deposition, chemical vapor deposition, and others. An exemplary method is sol-gel spin or dip coating which offers a possibility to vary the material composition of each thin layer easily. As a natural extension, a channel waveguide with a graded refractive index distribution in the vertical direction and a step refractive index distribution in the horizontal/lateral direction can be fabricated by etching a stripe **1815** in the film **1805**; the result of etching is shown in Fig. 30B. If a surrounding cladding is preferred, a subsequent deposition of a cladding material **1820** can always be performed.

Method 2: Another approach to make a step refractive index distribution in the lateral direction is to first deposit a photosensitive vertically graded refractive index film **1825** on the SiO_2 **1810**, as shown in Fig. 30C. In the case of silica-based glass, typically, Ge or Pb can be incorporated to make the glass film photosensitive. After the deposition of such a film **1825,** UV photo-imprinting through a conventional channel photomask **1830** can be used to induce a nearly step refractive index distribution in the lateral direction to form the channel waveguide **1835**.

If an upper cladding is preferred, a film **1840** with a refractive index lower than that of the photoimprinted stripe can then be deposited as shown in Fig. 30D. Alternatively, such a film can even be deposited before the UV photoimprinting as long as this upper cladding film does not substantially absorb the UV light. An obvious advantage of

the photoimprinting approach is that the fabrication of a buried channel waveguide is significantly simplified as it does not involve etching and hence the fabrication cost is also significantly lowered.

Either method produces a buried channel waveguide that has a step refractive index distribution in the horizontal/lateral direction and a graded refractive index distribution in the vertical direction.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1800** and are not intended to limit other embodiments of any exemplary device, or the device **1800**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces. of the present invention

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the said devices.

It should be understood to those skilled in the art that the device 1800 can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(B) A COMPOSITE-LATERAL-GRADED-REFRACTIVE-INDEX AND VERTICAL-GRADED-REFRACTIVE INDEX (LGRIN×VGRIN) ICMT DEVICE

Fig. 31 illustrates an alternative embodiment of an ICMT device **1850** including a vertical as well as a lateral graded refractive index distribution to form a channel waveguide. The device **1850** can perform as a two dimensional beam-size collimating element in both the lateral and the vertical directions for a propagating optical beam and can, for example, confine and collimate an optical beam that has already been partially expanded or enlarged from a small semiconductor waveguide via a tapered structure such as any of exemplary devices 1-4. The device is not limited to use as a beam collimator but can also function as a waveguide to direct a light beam to a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **1850** are intended to illustrate the uses for device **1850** and are not intended to limit the applications of other embodiments of device **1850**. The device can be referred to as a "composite-lateral-graded-refractive-index and vertical-graded-refractive index" (LGRIN×VGRIN) ICMT.

LGRIN×VGRIN ICMT **1850** preferably includes a waveguiding core region occupied by Waveguide Core WC **1885**. Waveguide Core WC **1885** is surrounded at the bottom by Lower Waveguide Cladding LWCL **1860**, on the top by Upper Waveguide Cladding UWCL **1890** and on both sides by Side Waveguide Cladding SWCL **1875**. Waveguide Core **1885** preferably includes a front beam input/output port FB-PT **1881**, a straight waveguiding core region SWC **1885**, and a back beam input/output port BB-PT **1882**. The straight waveguiding core region SWC **1885** has a length l_{SWC}, a width of w_{SWC} and a thickness of t_{SWC}. The Lower Waveguide Cladding LWCL **1860** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. The Upper Waveguide Cladding UWCL **1890** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The two side waveguide claddings SWCL **1875** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **1860/1890/1875**, l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the waveguide core l_{WC}. The refractive index of the Waveguide Core WC **1885** is not a constant. In both the vertical and the lateral directions, it is graded and varies from the center of the core to the outer borders of the core. The variation can be represented in the vertical direction by $n_{WC}(y)$ with y being the vertical coordinate and in the lateral direction by $n_{WC}(x)$ with x being the lateral coordinate. The refractive index of the

Lower Waveguide Cladding LWCL **1860** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **1890** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **1875** is $n_{SWCL}(y)$, which means it can be y coordinate dependent.

In an exemplary device, the front beam input/output port FB-PT **1881** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that is already enlarged to an intermediate size by a high-refractive-contrast tapered waveguide, and the back beam input/output port LB-PT **1882** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the Waveguide Core WC **1885** is made up of lead-titania-silica with a refractive index distribution that approximates a parabolic distribution in both the vertical and the lateral directions as given by the equation

$$n_{WC}(x,y) = 1.61 + 0.09\left[1 - \left(\frac{x^2 + y^2}{(5\mu m)^2}\right)\right].$$

The Lower Waveguide Cladding LWCL **1860** is made up of silica with a refractive index of $n_{LWCL} = 1.5$. The Upper Waveguide Cladding UWCL is made up of silica-titania with a refractive index of $n_{UWCL} = 1.6$. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index distribution given by Table I (above). The size of the waveguide core is $l_{WC} = 50$ μm, $w_{WC} = 10$ μm and $t_{WC} = 10$ μm. The size of the lower waveguide cladding is $l_{LWCL} = 50$ μm, $w_{LWCL} = 30$ μm and $t_{LWCL} = 10$ μm. The size of the upper waveguide cladding is $l_{UWCL} = 50$ μm, $w_{UWCL} = 30$ μm and $t_{UWCL} = 10$ μm. The size of the two side waveguide claddings is $l_{SWCL} = 50$ μm, $w_{SWCL} = 10$ μm and $t_{SWCL} = 10$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 32 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at $\lambda = 1.5$ μm after propagating into waveguide **1885**. The mode size at the input end is 10 μm in both the lateral and vertical directions. In both the vertical and the lateral directions, in addition to the guiding of the light

beam, the waveguide also functions as a lens in the sense that the beam size get focused and collimated periodically.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating LGRIN×VGRIN ICMT device **1850** will now be described with reference to Fig. 33A-B. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The LGRIN×VGRIN ICMT can be fabricated by starting with a Silica-On-Silicon (SOS) wafer that can be fabricated via a commercial process known to those skilled in the art. For a SOS wafer, as illustrated in Fig. 33A, a low refractive index layer of SiO_2 **1860** with a thickness of t_{LWCL} is already made on the Si substrate (not shown). The fabrication of the LGRIN×VGRIN ICMT according to one embodimentbelow.

As shown in Fig 33A, a graded refractive index distribution in the vertical direction can be achieved by depositing a multiple sufficiently thin layers of photosensitive materials with different compositions **1855** on a lower cladding layer **1860**. In such a case, a continuous distribution of the refractive index can be approximated by a series of small effective refractive index steps with each thin layer having a different refractive index value. Depending on the property of the dielectric material, an appropriate film deposition method can be used. These methods include evaporation, flame hydrolysis, sputtering, Ion-Assisted-Deposition, chemical vapor deposition, and others. An exemplary method is sol-gel spin or dip coating which offers a possibility to vary the material composition of each thin layer easily. In the case of silica-based glass, the photosensitivity of the glass material can be enabled by incorporating Ge or Pb into the glass film as set forth above.

As for the graded refractive index distribution in the lateral direction, it can be created by using a gray scale mask **1880** to optically imprint a graded refractive index change in the film because the refractive index change can be made to depend on the dosage of the photoimprinting which can be controlled by the gray scale of the gray mask. If an upper cladding **1890** is preferred, such a film can then be deposited on top of the photosensitive film, as shown in Fig. 33B. Alternatively, such an upper cladding film **1890** can be deposited before the UV photoimprinting as long as it does not substantially absorb the photoimprinting light. The approaches described here are obviously advantageous because of their simplicity

in terms of fabrication as set forth above. Alternatively, a vertical refractive index variation can be achieved by varying the amount of photosensitive materials such as the Ge or Pb content in the vertical direction. In this case, the UV photoimprinting described above will result in vertical refractive index variation in addition to the lateral refractive index variation.

The resulting device is a buried channel waveguide that has a graded index distribution in the both the vertical and the lateral directions.

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1850** and are not intended to limit other embodiments of any exemplary device, or the device **1850**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces. of the present invention

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the said devices.

It should be understood to those skilled in the art that the device 1850 can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(7) EXEMPLARY DEVICE 7: A VERTICAL-SHARP-DOWN-TAPER-AND-LATERAL-GRADUAL-UP-TAPER-CASCADED-WITH-A-VERTICAL-GRADED-REFRACTIVE-INDEX-AND-LATERAL-STEP-REFRACTIVE-INDEX (VSDT×LGUT + VGRIN×LSRIN) ICMT DEVICE

Fig. 34A-B illustrates a seventh general embodiment of a combined module ICMT device **1900** including a vertical-sharp-down-taper and lateral-gradual-up-taper waveguide core embedded in and connected to a large channel waveguide with a nearly symmetric vertical graded refractive index and lateral step refractive index distribution. It is in fact one possible combination of a taper waveguide integrated with a lower refractive-index-contrast large-size channel waveguide. The device **1900** performs as a two dimensional beam-size enlargement and collimating element in both the lateral and the vertical directions for a propagating optical beam, and can, for example, enlarge and collimate an optical beam from a small semiconductor waveguide to a large beam size such as one with a beam size close to that of an optical fiber. The device is not limited to use as a beam enlarger/collimator but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device is used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **1900** are intended to illustrate the uses for device **1900** and are not intended to limit the applications of other embodiments of device **1900** to these examples. The device can be referred to as a "vertical-sharp-down-taper-and-lateral-gradual-up-taper-cascaded-with-a-vertical-graded-refractive-index-and-lateral-step-refractive-index (VSDT×LGUT + VGRIN×LSRIN) ICMT.

The present VSDT×LGUT + VGRIN×LSRIN ICMT **1900** preferably includes a Waveguiding Core region occupied by Waveguide Core WC **1945**. This Waveguide Core WC **1945** is embedded in an optical medium **1915/1950** that acts as the cladding for the Waveguide Core WC **1945** wherever the Waveguide Core WC **1945** exists, but at the same time the same optical medium **1915/1950** acts as a Lower Refractive index Contrast Waveguiding Core region. This Lower Refractive index Contrast Waveguiding Core region **1915/1950** is occupied by Waveguide Core LRCWC **1915/1950**, and is further surrounded by an even lower refractive index cladding region **1905/1955/1976**.

Waveguide Core WC **1945** is surrounded at the bottom by Lower Graded Waveguide Cladding LGWCL **1915**, on the top by Upper Graded Waveguide Cladding UGWCL **1950** and on both sides by Side Stratified Waveguide Cladding SSWCL **1970**,

which is basically a combination of the Lower Graded Waveguide Cladding LGWCL **1915** and the Upper Graded Waveguide Cladding UGWCL **1950**.

When viewed from the side, the Waveguide Core WC **1945** preferably includes a small beam input/output port SB-PT **1971a**, a straight waveguiding core region SWC **1972a**, a vertically tapered down region VTD **1973a**, and an intermediate beam output/input port region **1974a**. The straight waveguiding core region SWCa **1972a** has a length $l_{HRCSWCa}$, and a thickness of $t_{HRCSWCa}$. The vertically tapered down waveguiding core region VTDWC **1973a** has a length of $l_{HRCVTDWCa}$, a vertical thickness of $t_{HRCVTDWCaSB}$ at the small-beam input/output side, and a vertical thickness of $t_{HRCVTDCaLB}$ at the large-beam input/output side.

When viewed from the top, Waveguide Core **1945** preferably includes a small beam input/output port SB-PT **1971b**, a straight waveguiding core region SWC **1972b**, a laterally tapered up region LTU **1973b**, a wider straight waveguiding core region WSWC **1975** and a large beam output/input port region **1974b**. The straight high refractive index contrast waveguiding core region SWCb **1972b** has a length $l_{HRCSWCb}$, and a width of $w_{HRCSWCb}$. The laterally tapered up waveguiding core region LTUWC **1973b** has a length of $l_{HRCLTUWCb}$, a width of $w_{HRCLTUWCbSB}$ at the small-beam input/output side, and a width of $w_{HRCLTUCbLB}$ at the large-beam input/output side. The wider straight waveguide core region WSWC **1975** has a length of $l_{HRCWSWCb}$ and a width of $w_{HRCWSWCb} = w_{HRCLTUCbLB}$.

It should be understood that the straight waveguiding core regions **1972a** and **1972b** (based on whether the structure is viewed from the side or from the top), may have the same or a different length. Similarly, the vertically tapered down region **1973a** (when viewed from the top) and the laterally tapered up region **1973b** (when viewed from the side) may have the same or a different length. In other words, the vertical and lateral beam size transformation may be achieved independently or at the same time or with one slightly earlier than the other. Furthermore, the taper regions do not need to be symmetric with respect to the central axis and also the tapering up or down slope do not need to be straight and may be of any curve shape.

Lower-Refractive-index-Contrast-Waveguide Core LRCWC **1915/1950** preferably surrounds and embeds the Waveguide Core WC **1945**. When viewed from the side, the Lower Refractive index Contrast Waveguide Core LRCWC **1915/1950** is sandwiched at the bottom by a Lower Waveguide Cladding LWCL **1905**, and on the top by an Upper Waveguide Cladding UWCL **1955**. As the Lower-Refractive-index-Contrast-Waveguide Core LRCWC **1915/1950** has a graded refractive index distribution along the

vertical direction, it can take the intermediate size beam launched at the tip region **1974a** from the Waveguide Core WC **1945** and further expand the beam; after the beam has traveled a certain distance equivalent to the focal length of the graded refractive index lens structure, the beam will be collimated and reach the back large beam output/input port LB-PT **1977**, from where another single mode waveguide such as a single mode optical fiber will continue to guide the light beam. When viewed from the top, the LRCWC **1970** (i.e. **1915/1950**) is surrounded on both sides by Side Waveguide Cladding SWCL **1976**, (with lower refractive index when compared to the Waveguide Core LRCWC **1970**). The Lower Refractive index Contrast Waveguide Core LRCWC **1970** has a length of l_{LRCWC}, a width of w_{LRCWC} and a thickness of t_{LRCWC}. The Lower Waveguide Cladding LWCL **1905** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. The Upper Waveguide Cladding UWCL **1955** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The two side waveguide claddings SWCL **1976** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **1905/1955/1976**, l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the lower refractive index contrast waveguide core l_{LRCWC}.

The refractive index of the Waveguide Core WC **1945** is n_{HRCWC}. The refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **1915/1950** is $n_{LRCWC}(y)$, which means it is y coordinate dependent, with y being the vertical coordinate. The refractive index of the Lower Waveguide Cladding LWCL **1905** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **1955** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **1976** is $n_{SWCL}(y)$, which means it can also be y coordinate dependent. It should be understood that the Side Waveguide Cladding SWCL **1976** can have either a uniform or non-uniform refractive index distribution. In other words, the refractive index of the Side Waveguide Cladding may or may not be a constant. In the latter case, it can be graded in the vertical direction. In device **1900**, as in exemplary device 6, the refractive index of the Waveguide Core LRCWC **1915/1950** is not a constant. It is graded in the vertical direction and varies from the center plane of the core to the top and bottom border of the core. The variation can be represented by $n_{LRCWC}(y)$ with y being the vertical coordinate. In the horizontal or lateral direction, the refractive index may have a step profile. In other words, for a given vertical coordinate y_0, the refractive index is a constant, $n_{LRCWC}(y_0)$, within the core region and drops at the two side borders to the refractive index value of the side cladding, $n_{SWCL}(y_0)$.

In an exemplary device, the front beam input/output port FB-PT **1971a/1971b** is configured to receive/transmit a light beam typically having wavelength λ with a very small beam size. The mode size of the straight section of the Waveguide Core WC **1945** can be designed to match the mode size of a preceding very small size waveguide. The laterally tapering up section of the WC **1945** will enlarge the beam fully in the lateral direction and the vertical tapering down section will partially enlarged the beam in the vertical direction to an intermediate size. The vertically graded Lower Refractive index Contrast Waveguide Core LRCWC is configured to take the vertically intermediate size beam launched at region **1974a** and further expand and collimate it. The back beam input/output port LB-PT **1977** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the High Refractive index Contrast Waveguide Core WC **1945** is made up of silicon with a refractive index of $n_{HRCWC} = 3.5$, the Low Refractive index Contrast Waveguide Core LRCWC **1915/1950** is made up of lead-titania-silica material mixture with a mixture composition to achieve a refractive index of a refractive index distribution that approximates a parabolic distribution as given in Table II below.

Table II Refractive index distribution

y coordinate (μm)	Refractive index of LRCWC	Refractive index of SWCL
-5.0 to –4.6	1.610	1.600
-4.6 to –4.2	1.624	1.614
-4.2 to –3.8	1.636	1.626
-3.8 to –3.4	1.648	1.638
-3.4 to –3.0	1.658	1.648
-3.0 to –2.6	1.668	1.658
-2.6 to –2.2	1.676	1.666
-2.2 to –1.8	1.683	1.673
-1.8 to –1.4	1.688	1.678
-1.4 to –1.0	1.693	1.683
-1.0 to –0.6	1.696	1.686
-0.6 to –0.2	1.699	1.689
-0.2 to 0.2	1.700	1.690
0.2 to 0.6	1.699	1.689
0.6 to 1.0	1.696	1.686
1.0 to 1.4	1.693	1.683
1.4 to 1.8	1.688	1.678

1.8 to 2.2	1.683	1.673
2.2 to 2.6	1.676	1.666
2.6 to 3.0	1.668	1.658
3.0 to 3.4	1.658	1.648
3.4 to 3.8	1.648	1.638
3.8 to 4.2	1.636	1.626
4.2 to 4.6	1.624	1.614
4.6 to 5.0	1.610	1.600

The Lower Waveguide Cladding LWCL **1905** is made up of silica-titania with a refractive index of n_{LWCL} = 1.5. The Upper Waveguide Cladding UWCL is made up of silica-titania with a refractive index of n_{UWCL} = 1.5. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index distribution also given in Table II.

The dimensions of the Waveguide Core WC **1945** are as follows: $l_{HRCSWCa}$ = 110 μm, $t_{HRCSWCa}$ = 0.3 μm, $l_{HRCVTDWCa}$ = 30 μm, $t_{HRCVTDWCaSB}$ = 0.3 μm, $t_{HRCVTDCaLB}$ = 0 μm, $l_{HRCSWCb}$ = 10 μm, $w_{HRCSWCb}$. = 0.3 μm, $l_{HRCLTUWCb}$ = 100 μm, $w_{HRCLTUWCbSB}$ = 0.3 μm, $w_{HRCLTUCbLB}$ = 10 μm, $l_{HRCWSWCb}$ = 30 μm and $w_{HRCWSWCb}$ = 10 μm. The dimensions of the Lower Refractive index Contrast Waveguide Core LRCWC **1915/1950** are as follows: l_{LRCWC} = 170 μm, w_{LRCWC} = 10 μm, t_{LRCWC} = 10 μm. The Lower Waveguide Cladding LWCL **1905** has a length of l_{LWCL} = 170 μm, a width of w_{LWCL} = 30 μm and a thickness of t_{LWCL} = 2 μm. The Upper Waveguide Cladding UWCL **1955** has a length of l_{UWCL} = 170 μm, a width of w_{UWCL} = 30 μm and a thickness of t_{UWCL} = 2 μm. The two side waveguide claddings SWCL **1976** have a length of l_{SWCL} = 170 μm, a width of w_{SWCL} = 10 μm and a thickness of t_{SWCL} = 10 μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 35 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at λ = 1.5 μm after being launched from the left into the small light beam input/output port **1971a/1971b**. The mode size at the input end is 0.3 μm in both the lateral and vertical directions. In the vertical direction, as the tapering down section only lies towards the right for the last 30 μm and the cascading beam expansion action occurs on both the left and the right part of the WC taper tip, the computer simulation is thus zoomed into the last 60 μm of the coupler structure. In the lateral direction, the beam expansion is entirely enabled by the tapering up section **1973b**, which has a length of 100

μm, hence the computer simulation is zoomed mainly in this section. As can be seen from FIG. 35, the combined module coupler structure can transform a very small beam of about 0.3 μm in size to a large size beam of about 10 μm in both the vertical and the horizontal directions.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating a HRC-VSDT×LGUT+VGRIN×LSRIN ICMT device **1900** will now be described with reference to Fig. 36A-N. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The HRC-VSDT×LGUT+VGRIN×LSRIN ICMT **1900** may be fabricated by starting with a Silica-On-Silicon (SOS) wafer shown in Fig. 36A, which may be fabricated via a commercial process known to those skilled in the art. For a SOS wafer, a low refractive index layer of SiO_2 **1905** with a thickness of t_{LWCL} is already made on a Si substrate **1910**. The fabrication of the HRC-VSDT×LGUT+VGRIN×LSRIN ICMT structure according to one embodiment now described below.

As shown in Fig 36B-C, a graded index distribution in the vertical direction can be achieved by depositing multiple sufficiently thin layers of photosensitive materials with different compositions **1915** on a lower cladding layer **1905**. In such a case, a continuous distribution of the refractive index can be approximated by a series of small refractive index steps with each thin layer having a different refractive index value. Depending on the property of the dielectric material, an appropriate film deposition method can be used. These methods include evaporation, flame hydrolysis, sputtering, Ion-Assisted-Deposition, chemical vapor deposition, and others. An exemplary method is sol-gel spin or dip coating which offers a possibility to vary the material composition of each thin layer easily. In the case of silica-based glass, the photosensitivity of the glass material can be enabled by incorporating Ge or Pb into the glass film. It should be understood that any optically transparent dielectric material in the spectrum region of interest to optical communication can be used for the deposition; examples include lead silica, germania-silica, titania-silica, silicon oxynitride, silicon nitride, polysilicon, silicon-rich-silica, silicon carbide, polymer and a combination of different materials. The parameter details of one exemplary

embodiment of the design for the GRIN layers has already been shown in Table II. Note that the refractive index distribution does not have to follow the parabolic profile and may be of any profile. It should also be understood that other film deposition techniques such as flame hydrolysis, sputtering, Ion-Assisted-Deposition and chemical vapor deposition may also be used to deposit the bottom half of the GRIN dielectric waveguide.

As shown in Fig. 36D, a thin silicon layer **1920,** which is to be made into the high refractive index contrast waveguide core WC **1945**, may be defined in another piece of bare Si wafer using, for example, ion implantation. A thin silicon layer **1920** is formed on an ion implanted layer **1925** that is sitting on top of a Si substrate **1930.** This ion-implanted wafer may then be flipped over and wafer-bonded to the GRIN dielectric-coated SiO_2-Si wafer, as shown in Fig. 36E. The top thick Si part **1930** and the ion-implanted layer **1925** may then be removed using a lift-off technique such as rapid thermal annealing and/or wafer thinning. The result after removing the ion-implanted layer is shown in Fig. 36F. This technique may be modified if, for instance, a non-symmetric vertical-GRIN waveguide is desired, as will be described below.

To form a vertically down-tapered and horizontally/laterally up-tapered high-index core, the fabrication steps described with regard to Exemplary device 4 may be used. In short, a photoresist layer is first spin-coated on the Si waveguide layer **1920.** A mask pattern **1935** with a gray-scaled transparency along the longitudinal direction, and a horizontal/lateral up taper, shown in Fig. 36G, can be used together with UV exposure and photoresist development to make a vertically tapered down and horizontally/laterally tapered up photoresist pattern **1940**, shown in Fig. 36H. The lateral and vertical tapers may be made independent from each other, although in Fig. 36H, they have been put together to save space and also to illustrate the principle. Followed by dry etching, as indicated in Fig. 36I, the vertically down tapered and horizontally/laterally up tapered photoresist pattern **1940** is transferred to the high refractive index Si layer to form the vertically down-tapered and horizontally/laterally up-tapered Si section **1945**, as shown in Fig. 36J-K. As was previously noted, the interface between the top Si layer and the SiO_2 based layer may be used as a natural stop during the dry etching process. It should also be noted that a shadow mask based dry etching process or a diffusion-limited wet etching process could also be used to form the Si taper as well.

To form the top half of the vertically GRIN dielectric waveguide part, an effective refractive-index-decreasing dielectric region **1950** is deposited, as shown in Fig. 36L. Preferably photosensitive sol-gel silica is spin-coated in almost the same way as for the

bottom half of the dielectric waveguide except that the order of the layers is now reversed. It should again be understood that the parabolic refractive index distribution cited here is only one example and, as is well known to those skilled in the art, various other refractive index distributions may be used. On the very top, a relatively thick (say 2 μm) silica layer **1955** can be deposited to act as an upper cladding.

Note that the sol-gel technique has an advantage in that the spin-coated film will change shape from conformal coating to planarized coating. The initial layer thickness may not be so even and uniform. However, due to the fact that the Si taper **1945** is generally only about 0.2~0.5 μm high, after a few spin-on layers, the following layers should be flat and uniform as suggested in Fig. 36L. With a top cladding **1955**, a buried GRIN planar waveguide **1915/1950** is thus formed with the Si taper **1945** in the center of the GRIN waveguide core.

To form a dielectric channel waveguide with a step refractive index distribution in the lateral direction to confine light propagation, dry etching can be used. However, UV imprinting is preferred since the deposited GRIN dielectric film can be made photosensitive. A step channel mask **1960**, as shown in Fig. 36M, can be used to form a single mode step refractive index channel waveguide **1965** to confine light in the horizontal/lateral direction. When viewed from the top, as shown in Fig. 36N, the result is a tapered up Si taper **1945** integrated with a step index channel waveguide **1965.**

It should be understood that these dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **1900** and are not intended to limit other embodiments of any exemplary device, or the device **1900**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the various embodiments of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces. of the present invention

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the said devices.

It should be understood to those skilled in the art that the device 1900 can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(8) EXEMPLARY DEVICE 8: A VERTICAL-SHARP-DOWN-TAPER-AND-LATERAL-SHARP-DOWN-TAPER-CASCADED-WITH-A-SYMMETRIC-VERTICAL-GRADED-REFRACTIVE-INDEX-AND-LATERAL-GRADED-REFRACTIVE-INDEX (VSDT×LSDT+VGRIN×LGRIN) ICMT DEVICE

Fig. 37A-B illustrates an eighth general embodiment of a combined module ICMT device **2000** including a vertically and laterally down-tapered waveguide core embedded in and connected to a large channel waveguide with a nearly symmetric vertically and laterally graded refractive index distribution. It is in fact a second possible combination of a taper integrated with a lower -refractive-index-contrast large-size channel waveguide. The device **2000** can perform as a two dimensional beam-size enlargement and collimating element in both the lateral and the vertical directions for a propagating optical beam, and can in particular enlarge and collimate an optical beam from a small semiconductor waveguide to enable the beam to match with a single mode optical fiber. The device is not limited to use as a beam enlarger/collimator but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **2000** are intended to illustrate the uses for device **2000** and are not intended to limit the applications of other embodiments of device **2000**. The device can be referred to as a

"vertical-sharp-down-taper and lateral-sharp-down-taper-cascaded-with-a-symmetric-vertical-graded-refractive-index-and-lateral-graded-refractive-index (VSDT×LSDT + VGRIN×LGRIN) ICMT".

VSDT×LSDT + VGRIN×LGRIN ICMT **2000** preferably includes a Waveguiding Core region occupied by Waveguide Core WC **2045**. This Waveguide Core WC **2045** is embedded in an optical medium **2015/2050** that acts as the cladding for the Waveguide Core WC **2045** wherever the Waveguide Core WC **2045** exists, but at the same time, the same optical medium **2015/2050** acts as a Lower Refractive index Contrast Waveguiding Core region. This Lower Refractive index Contrast Waveguiding Core region is occupied by Waveguide Core LRCWC **2015/2050**, and is further surrounded by an even lower refractive index cladding region **2005/2055/2076**.

Waveguide Core WC **2045** is surrounded at the bottom by Lower Graded Waveguide Cladding LGWCL **2015**, on the top by Upper Graded Waveguide Cladding UGWCL **2050** and on both sides by Side Stratified Waveguide Cladding SSWCL **2070**, which is basically a combination of the Lower Graded Waveguide Cladding LGWCL **2015** and the Upper Graded Waveguide Cladding UGWCL **2050**.

When viewed from the side, the Waveguide Core WC **2045** preferably includes a small beam input/output port SB-PT **2071a**, a high refractive index contrast straight waveguiding core region SWC **2072a**, a high refractive index contrast vertically tapered down region VTD **2073a**, and an intermediate beam output/input port region **2074a**. The straight high refractive index contrast waveguiding core region SWCa **2072a** has a length $l_{HRCSWCa}$, and a thickness of $t_{HRCSWCa}$. The high refractive index contrast vertically tapered down waveguiding core region VTDWC **2073a** has a length of $l_{HRCVTDWCa}$, a vertical thickness of $t_{HRCVTDWCaSB}$ at the small-beam input/output side, and a vertical thickness of $t_{HRCVTDCaLB}$ at the large-beam input/output side.

When viewed from the top, the Waveguide Core **2045** preferably includes a small beam input/output port SB-PT **2071b**, a straight waveguiding core region SWC **2072b**, a laterally tapered down region LTD **2073b**, and an intermediate beam output/input port region **2074b**. The straight waveguiding core region SWCb **1972b** has a length $l_{HRCSWCb}$, and a width of $w_{HRCSWCb}$. The laterally tapered down waveguiding core region LTDWC **1973b** has a length of $l_{HRCLTDWCb}$, a width of $w_{HRCLTDWCbSB}$ at the small-beam input/output side, and a width of $w_{HRCLTDCbLB}$ at the large-beam input/output side.

It should be understood that the straight waveguiding core regions **2072a** and **2072b** (based on whether the structure is viewed from the side or from the top), may have the same or a different length. Similarly, the vertically tapered down region **2073a** (when viewed from the side) and the laterally tapered down region **2073b** (when viewed from the side) may have the same or a different length, provided that the tip for both tapering down geometries ends at the same point in space. Furthermore, the taper regions do not need to be symmetric with respect to the central axis and also the tapering down slopes do not need to be straight and may be of any curve shape.

Lower-Refractive-index-Contrast-Waveguide Core LRCWC **2015/2050** preferably surrounds and embeds the Waveguide Core WC **2045**. When viewed from the side, the Lower Refractive index Contrast Waveguide Core LRCWC **2015/2050** is sandwiched at the bottom by a Lower Waveguide Cladding LWCL **2005**, and on the top by an Upper Waveguide Cladding UWCL **2055**. As the Lower-Refractive-index-Contrast-Waveguide Core LRCWC **2015/2050** has a graded refractive index distribution along both the vertical and lateral directions, it can take the intermediate size beam launched at the tip region **2074a/2074b** from the Waveguide Core WC **2045** and further expand the beam. After the beam has traveled a certain distance equivalent to the focal length of the graded refractive index lens structure, the beam will be collimated and reach the back large beam output/input port LB-PT **2077**, from where another single-mode waveguide such as a single-mode optical fiber will continue to guide the light beam. The Lower Refractive index Contrast Waveguide Core LRCWC **2070** has a length of l_{LRCWC}, a width of w_{LRCWC} and a thickness of t_{LRCWC}. The Lower Waveguide Cladding LWCL **2005** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. The Upper Waveguide Cladding UWCL **2055** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The two side waveguide claddings SWCL **2076** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **2005/2055/2076,** l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the low refractive index contrast waveguide core l_{LRCWC}.

The refractive index of the Waveguide Core WC **2045** is n_{HRCWC}. The refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **2015/2050** is $n_{LRCWC}(x, y)$, which means it is x and y coordinate dependent, with x being the lateral coordinate and y being the vertical coordinate. The refractive index of the Lower Waveguide Cladding LWCL **2005** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **2055** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **2076** is $n_{SWCL}(y)$, which means it may also be y-coordinate dependent. It should be understood that

the Side Waveguide Cladding SWCL **2076** may have either a uniform or non-uniform refractive index distribution. In other words, the refractive index of the Side Waveguide Cladding may or may not be a constant. In the latter case, it may be graded in the vertical direction. In a preferred embodiment, the refractive index of the Waveguide Core LRCWC **2015/2050** is not a constant. It is graded in the vertical direction and varies from the center plane of the core to the top and bottom border of the core. The variation can be represented by $n_{LRCWC}(y)$ with y being the vertical coordinate. In the lateral direction, the refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **2070** also have a graded profile. However, for a given vertical coordinate y_0, the refractive index $n_{LRCWC}(x, y_0)$ is graded within the core region and drops to $n_{SWCL}(y_0)$, the refractive index value of the side cladding at the two side borders.

In an exemplary device, the front beam input/output port FB-PT **2071a/2071b** is configured to receive/transmit a light beam typically having wavelength λ with a very small beam size. The mode size of the straight section of the Waveguide Core WC **2045** can be designed to match the mode size of a preceding very-small-size waveguide. The laterally and vertically tapering down section **2073a/2073b** will partially enlarge the beam in both the vertical and the lateral directions to an intermediate size. The laterally and vertically graded Lower Refractive index Contrast Waveguide Core LRCWC is configured to take the intermediate size beam launched at region **2074a/2074b** and further expand and collimate it. The back beam input/output port LB-PT **2077** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the Waveguide Core WC **2045** is made up of silicon with a refractive index of $n_{HRCWC} = 3.5$, the Lower Refractive index Contrast Waveguide Core LRCWC **2015/2050** is made up of lead-titania-silica material mixture with mixture composite designed to give a refractive index distribution that approximates a parabolic distribution in both the vertical and the lateral directions as given by the equation:

$$n_{LRCWC}(x,y) = 1.61 + 0.09\left[1 - \left(\frac{x^2 + y^2}{(5\mu m)^2}\right)\right].$$

The Lower Waveguide Cladding LWCL **2005** is made up of silica-titania with a refractive index of $n_{LWCL} = 1.5$. The Upper Waveguide Cladding UWCL is made up of

silica-titania with a refractive index of $n_{UWCL} = 1.5$. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index distribution given in Table II.

The dimensions of the Waveguide Core WC **2045** are as follows: $l_{HRCSWCa} = 10$ µm, $t_{HRCSWCa} = 0.3$ µm, $l_{HRCVTDWCa} = 30$ µm, $t_{HRCVTDWCaSB} = 0.3$ µm, $t_{HRCVTDCaLB} = 0$ µm, $l_{HRCSWCb} = 10$ µm, $w_{HRCSWCb} = 0.3$ µm, $l_{HRCLTDWCb} = 30$ µm, $w_{HRCLTDWCbSB} = 0.3$ µm, $w_{HRCLTDCbLB} = 0$ µm. The dimensions of the Lower Refractive index Contrast Waveguide Core LRCWC **2015/2050** are as follows: $l_{LRCWC} = 70$ µm, $w_{LRCWC} = 10$ µm, $t_{LRCWC} = 10$ µm. The Lower Waveguide Cladding LWCL **2005** has a length of $l_{LWCL} = 70$ µm, a width of $w_{LWCL} = 30$ µm and a thickness of $t_{LWCL} = 2$ µm. The Upper Waveguide Cladding UWCL **2055** has a length of $l_{UWCL} = 70$ µm, a width of $w_{UWCL} = 30$ µm and a thickness of $t_{UWCL} = 2$ µm. The two side waveguide claddings SWCL **2076** have a length of $l_{SWCL} = 70$ µm, a width of $w_{SWCL} = 10$ µm and a thickness of $t_{SWCL} = 10$ µm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 38 shows the results of a computer simulation of the spatial distribution of the electric field strength for the light input at $\lambda = 1.5$ µm after being launched from the left into the small light beam input/output port **2071a/2071b**. The mode size at the input end is 0.3 µm in both the lateral and vertical directions. As the tapering down section only lies towards the right for the last 30 µm in both the vertical and the lateral directions and the cascading beam expansion action occurs on both the left and the right part of the WC taper tip, the computer simulation is thus zoomed into the last 60 µm of the coupler structure. Although the computer simulation is only 2 dimensional, it can be applied to both the vertical and the lateral directions because the structures are very similar in this case. As can be seen from FIG. 38, the whole combined module coupler structure can transform a very small beam of 0.3 µm in size to a large size beam of 10 µm in both the vertical and the horizontal directions.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating a VSDT×LSDT+VGRIN×LGRIN ICMT device **2000** will now be described with reference to Fig. 39A-N. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can

be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The VSDT×LSDT+VGRIN×LGRIN ICMT may be fabricated by starting with a Silica-On-Silicon (SOS) wafer, shown in Fig. 39A, which may be fabricated via a commercial process known to those skilled in the art. For an SOS wafer, a low refractive index layer of SiO_2 **2005** with a thickness of t_{LWCL} is already made on a Si substrate **2010**. The fabrication of the VSDT×LSDT+VGRIN×LGRIN ICMT structure according to one embodiment is now described below.

As shown in Fig 39B-C, a graded refractive index distribution in the vertical direction may be achieved by depositing multiple sufficiently thin layers of photosensitive materials with different compositions **2015** on a lower cladding layer **2005**. In such a case, a continuous distribution of the refractive index can be approximated by a series of small effective refractive index steps with each thin layer having a different refractive index value. Depending on the property of the dielectric material, an appropriate film deposition method can be used. These methods include evaporation, flame hydrolysis, sputtering, Ion-Assisted-Deposition, chemical vapor deposition, and others. An exemplary method is sol-gel spin or dip coating which offers the ability to vary the material composition of each thin layer easily. In the case of silica-based glass, the photosensitivity of the glass material may be enabled by incorporating Ge or Pb into the glass film. It should be understood that any optically transparent dielectric material in the spectrum region of interest to optical communication may be used for the deposition; examples include lead silica, germania-silica, titania-silica, silicon oxynitride, silicon nitride, polysilicon, silicon-rich-silica, silicon carbide, polymer and a combination of different materials. The parameter details of one preferred embodiment of the design for the GRIN layers has already been shown in Table II. Note that the refractive index distribution does not have to follow the parabolic profile and may be of any profile. It should also be understood that other film deposition techniques such as flame hydrolysis, sputtering, Ion-Assisted-Deposition and chemical vapor deposition may also be used to deposit the bottom half of the GRIN dielectric waveguide.

As shown in Fig. 39D, a thin silicon layer **2020**, which is to be made into the high index contrast waveguide core, may be defined in another piece of bare Si wafer using, for example, ion implantation. This will form a thin silicon layer **2020** on an ion implanted layer **2025** that is sitting on top of a Si substrate **2030**. This ion-implanted wafer may be flipped over and wafer-bonded to the GRIN dielectric-coated SiO_2-Si wafer, as shown in Fig.

39E. The top thick Si part **2030** and the ion-implanted layer **2025** may then be removed using a lift-off technique such as rapid thermal annealing and/or wafer thinning. The result is shown in Fig. 39F. This technique may be modified if, for instance, a non-symmetric vertical-GRIN waveguide is desired, as will be described below.

To form a vertically as well as horizontally/laterally tapered down section, the fabrication steps are similar to those described above for exemplary device 4. A photoresist layer is first spin-coated on the Si waveguide layer **2020**. A mask pattern **2035**, shown in Fig. 39G, with a gray scaled transparency along the longitudinal direction and meanwhile a horizontal/lateral down/narrow taper can be used together with UV exposure and photoresist development to make a vertically as well as horizontally/laterally down tapered photoresist pattern **2040**, as shown in Fig. 39H. Followed by dry etching, as shown in Fig. 39I, the vertically as well as horizontally/laterally down tapered photoresist pattern **2040** can be transferred to the high refractive index Si layer and form the vertically and horizontally/laterally tapered down/narrow Si section **2045**, as shown in Fig. 39J-K. It should again be noted that the interface between the top Si layer and the glass-based cladding material can be used as a natural stop during the dry etching process.

To form the top half of the vertically GRIN glass/polymer waveguide, a refractive-index-decreasing dielectric region **2050** is deposited as shown in Fig. 39L. Preferably photosensitive sol-gel silica is spin-coated in almost the same way as for the bottom half of the glass/polymer waveguide except that the order of the layers is now reversed. It should again be understood that the parabolic refractive index distribution cited here is only one example and, as is well known to those skilled in the art, other refractive index distributions may be used. On the very top, a relatively thick (say 3 μm) silica layer **2055** may be deposited to act as an upper cladding.

It should be noted that the sol-gel technique has an advantage in that the spin-coated film will change shape from conformal coating to planarized coating. The initial layer thickness may not be so even and uniform. However, due to the fact that the Si taper **2045** is generally only about 0.2~0.5 μm high, after a few spin-on layers, the following layers should be flat and uniform. With a top cladding **2055**, a buried GRIN planar waveguide **2015/2050** can thus be formed with the Si taper **2045** in the center of the GRIN waveguide core.

As has been described before, to form a dielectric channel waveguide with a GRIN distribution in the horizontal/lateral direction to confine light propagation, UV imprinting may be used since the deposited GRIN glass/polymer film may be made

photosensitive. A GRIN channel mask **2060**, as shown in Fig. 39M can be used to form a single mode GRIN channel waveguide **2065** to confine light in the horizontal/lateral direction, resulting in the structure shown in Fig. 39N.

It should be understood that the above dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **2000** and are not intended to limit other embodiments of any exemplary device, or the device **2000**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the various embodiments of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device **2000** can be fabricated on a different substrate other than silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(9) EXEMPLARY DEVICE 9: A VERTICAL-SHARP-DOWN-TAPER-CASCADED-WITH-A-NONSYMMETRIC-VERTICAL-GRADED-REFRACTIVE-INDEX-(VSDT+NSVGRIN) DEVICE

Fig. 40A-C illustrates a ninth general embodiment of a combined module ICMT device **2100** involving a vertically down-tapered waveguide core cascaded with and connected to a large channel waveguide with a non-symmetric vertically graded refractive index distribution. In the lateral direction, the high refractive index contrast taper can be either gradually tapered up, as shown in Fig. 40B, or sharply tapered down, as shown in Fig. 40C. In the former case, the large channel waveguide has a step index profile in the lateral direction. In the latter case, the large channel waveguide has a graded index profile. Device **2100** differs from exemplary device 7 or 8 in that the vertical GRIN waveguide in device **2100** is non-symmetric.

The device **2100** can perform as a two-dimensional beam-size enlargement and collimating element in both the lateral and the vertical directions for a propagating optical beam, and can in particular enlarge and collimate an optical beam from a small semiconductor waveguide to enable the beam to match with a single mode optical fiber. The device is not limited to use as a beam enlarger/collimator but can also function as a beam reducer when the optical beam propagates in the reverse direction. Furthermore, the device can be used for direct light beam coupling into an optical fiber. It should be understood that these exemplary applications of device **2100** are intended to illustrate the uses for device **2100** and are not intended to limit the applications of other exemplary embodiments of device **2100** to these examples. The device can be referred to as a "vertical-sharp-down-taper-cascaded-with-a-nonsymmetric-vertical-graded-refractive-index (VSDT+NSVGRIN) ICMT".

The present VSDT+NSVGRIN ICMT preferably includes a Waveguiding Core region occupied by Waveguide Core WC **2145/2150**. This Waveguide Core WC **2145/2150** is sandwiched at the bottom by a Lower Waveguide Cladding LWC **2110** and on the top as well as at both sides by a vertically graded refractive medium **2155** that acts as the top and side cladding for the Waveguide Core WC **2145/2150** wherever the Waveguide Core WC **2145/2150** exists. The same graded refractive index medium **2155** acts as a Lower Refractive Index Contrast Waveguiding Core region. This Lower Refractive index Contrast Waveguiding Core region is occupied by Waveguide Core LRCWC **2155**, and is further surrounded at the top by an even lower refractive index Upper Waveguide Cladding **2160**.

When viewed from the side, the Waveguide Core WC **2145/2150** preferably includes a small beam input/output port SB-PT **2171a**, a high refractive index contrast straight waveguiding core region SWC **2172a**, a high refractive index contrast vertically down-tapered region VTD **2173a**, and an intermediate beam output/input port region **2174a**. The straight high refractive index contrast waveguiding core region SWCa **2172a** has a length $l_{HRCSWCa}$, and a thickness of $t_{HRCSWCa}$. The high refractive index contrast vertically tapered down waveguiding core region VTDWC **2173a** has a length of $l_{HRCVTDWCa}$, a vertical thickness of $t_{HRCVTDWCaSB}$ at the small-beam input/output side, and a vertical thickness of $t_{HRCVTDCaLB}$ at the large-beam input/output side.

In the laterally up-tapering case, when viewed from the top, the Waveguide Core **2145** preferably includes a small beam input/output port SB-PT **2171b**, a straight waveguiding core region SWC **2172b**, a laterally up-tapered region LTU **2173b**, a wider straight waveguiding core region WSWC **2175** and a large beam output/input port region **2174b**. The straight waveguiding core region SWCb **2172b** has a length $l_{HRCSWCb}$, and a width of $w_{HRCSWCb}$. The laterally up-tapered waveguiding core region LTUWC **2173b** has a length of $l_{HRCLTUWCb}$, a width of $w_{HRCLTUWCbSB}$ at the small-beam input/output side, and a width of $w_{HRCLTUCbLB}$ at the large-beam input/output side. The wider straight waveguide core region WSWC **2175** has a length of $l_{HRCWSWCb}$ and a width of $w_{HRCWSWCb} = w_{HRCLTUCbLB}$.

In the laterally down-tapering case, when viewed from the top, the Waveguide Core **2150** preferably includes a small beam input/output port SB-PT **2171c**, a straight waveguiding core region SWC **2172c**, a laterally down-tapered region LTD **2173c**, and an intermediate beam output/input port region **2174c**. The straight waveguiding core region SWCc **2172c** has a length $l_{HRCSWCc}$, and a width of $w_{HRCSWCc}$. The laterally tapered down waveguiding core region LTDWC **2173c** has a length of $l_{HRCLTDWCc}$, a width of $w_{HRCLTDWCcSB}$ at the small-beam input/output side, and a width of $w_{HRCLTDCcLB}$ at the large-beam input/output side.

It should be understood that the straight waveguiding core regions **2171a** and **2171b/c** (based on whether the structure is viewed from the side or from the top), may have the same or a different length. Similarly, the vertically down-tapered region **2172a** (when viewed from the side) and the laterally up/down-tapered region **2172b/c** (when viewed from the side) may have the same or a different length, provided that in the case where the waveguide core is both laterally and vertically down-tapered, the tip for both down-tapering geometries ends at the same point in space. Furthermore, the taper regions do not need to be

symmetric with respect to the central axis and also the down-tapering slope (or slopes) do(es) not need to be straight and may be of any curve shape.

Lower-Refractive-index-Contrast-Waveguide Core LRCWC **2155** surrounds and embeds the Waveguide Core WC **2145/2150** either partially or entirely. When viewed from the side, the Lower Refractive index Contrast Waveguide Core LRCWC **2155** is sandwiched at the bottom by a Lower Waveguide Cladding LWCL **2110**, and on the top by an Upper Waveguide Cladding UWCL **2160**. As the Lower-Refractive-index-Contrast-Waveguide Core LRCWC **2155** has a graded refractive index distribution in the vertical direction, it can take a vertically intermediate size beam launched at the tip region **2174a** from the Waveguide Core WC **2145/2150** and further expand the beam. After the beam has traveled a certain distance equivalent to the focal length of the graded refractive index structure, the beam will be collimated and reach the back large beam output/input port LB-PT **2177**, from where another single mode waveguide such as a single mode optical fiber will continue to guide the light beam. The Lower Refractive index Contrast Waveguide Core LRCWC **2155** has a length of l_{LRCWC}, a width of w_{LRCWC} and a thickness of t_{LRCWC}. The Lower Waveguide Cladding LWCL **2110** has a length of l_{LWCL}, a width of w_{LWCL} and a thickness of t_{LWCL}. The Upper Waveguide Cladding UWCL **2160** has a length of l_{UWCL}, a width of w_{UWCL} and a thickness of t_{UWCL}. The side waveguide claddings SWCL **2176b/c** have a length of l_{SWCL}, a width of w_{SWCL} and a thickness of t_{SWCL}. The lengths of the waveguide claddings LWCL/UWCL/SWCL **2005/2055/2076**, l_{LWCL}, l_{UWCL}, and l_{SWCL} are about equal to the length of the low refractive index contrast waveguide core l_{LRCWC}.

The refractive index of the Waveguide Core WC **2145/2150** is n_{HRCWC}. The refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **2155** is $n_{LRCWC}(x, y)$, which means that it may be x- and y-coordinate dependent, with x being the lateral coordinate and y being the vertical coordinate. The refractive index of the Lower Waveguide Cladding LWCL **2110** is n_{LWCL}. The refractive index of the Upper Waveguide Cladding UWCL **2160** is n_{UWCL}. The refractive index of the Side Waveguide Cladding SWCL **2176b/c** is $n_{SWCL}(y)$, which means it may also be y coordinate dependent. It should be understood that the Side Waveguide Cladding SWCL **2176b/c** may have either a uniform or non-uniform refractive index distribution. In other words, the refractive index of the Side Waveguide Cladding may or may not be a constant. In the latter case, it may be graded in the vertical direction. Similar to exemplary device 6, the refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **2155** is preferably not a constant. It is graded in the vertical direction and varies from the bottom to the top. The variation can be

represented by $n_{LRCWC}(y)$, with y being the vertical coordinate. In the lateral direction, the refractive index of the Lower Refractive index Contrast Waveguide Core LRCWC **2155** may have either a step or a graded profile. In the step profile case, for a fixed y value, the refractive index $n_{LRCWC}(x, y)$ has a fixed higher value within the core region and a lower value outside the core region. For the graded profile case, for a given y coordinate y_0, the refractive index $n_{LRCWC}(x, y_0)$ is graded within the core region and drops to $n_{SWCL}(y_0)$, the refractive index value of the side cladding, at the two side borders.

In an exemplary device, the front beam input/output port FB-PT **2171a/b/c** is configured to receive/transmit a light beam typically having wavelength λ with a very small beam size. The mode size of the straight section **2172a/b/c** of the Waveguide Core WC **2145/2150** is preferably designed to match the mode size of a preceding very small size waveguide. The vertically down-tapering section **2173a** will partially enlarge the beam in the vertical direction to an intermediate size. The vertically graded Lower Refractive index Contrast Waveguide Core LRCWC **2155** is configured to take the intermediate size beam launched at region **2174a** and further expand and collimate it. Note that in device **2100**, only the top half of a symmetric GRIN waveguide is fabricated on top of the Waveguide Core taper. The consequence is that the refractive index distribution is no longer symmetric in the vertical direction (Note that in the lateral direction across a channel waveguide, the refractive index distribution can still be made symmetric using, e.g.,UV imprinting as has been explained). The coupler is functional because the situation is equivalent to using half of a lens with the Si taper located on the central axis of the lens. The lateral beam enlargement for both the laterally up tapering and down tapering cases is substantially the same as has been described for exemplary devices 7 and 8 and will thus not be repeated. The back beam input/output port LB-PT **2177** is configured to receive/transmit a light beam typically having wavelength λ with a beam size that roughly equals the size of an optical fiber.

(i) An Exemplary Device

In an exemplary embodiment, the Waveguide Core WC **2145/2150** is made up of silicon with a refractive index of $n_{HRCWC} = 3.5$. The Lower Refractive index Contrast Waveguide Core LRCWC **2155** is made up of lead-titania-silica material mixture with mixture composite designed to give a refractive index distribution that approximates half of a parabolic distribution in the vertical direction as governed by the following equation and detailed in Table III.

$$n_{LRCWC}(y) = 1.65 + 0.3\left[1 - \left(\frac{y^2}{(10\mu m)^2}\right)\right], \quad y \geq 0$$

Table III The refractive index profile of a high focusing power 10 μm height half GRIN waveguide

coordinate y (μm)	LRCWC refractive index n	SWCL refractive index n
0.0 – 0.4	1.950	1.940
0.4 – 0.8	1.948	1.938
0.8 – 1.2	1.946	1.936
1.2 – 1.6	1.942	1.932
1.6 – 2.0	1.938	1.928
2.0 – 2.4	1.933	1.923
2.4 – 2.8	1.926	1.916
2.8 – 3.2	1.919	1.909
3.2 – 3.6	1.911	1.901
3.6 – 4.0	1.902	1.892
4.0 – 4.4	1.892	1.882
4.4 – 4.8	1.881	1.871
4.8 – 5.2	1.869	1.859
5.2 – 5.6	1.856	1.846
5.6 – 6.0	1.842	1.832
6.0 – 6.4	1.827	1.817
6.4 – 6.8	1.811	1.801
6.8 – 7.2	1.794	1.784
7.2 – 7.6	1.777	1.767
7.6 – 8.0	1.758	1.748
8.0 – 8.4	1.738	1.728
8.4 – 8.8	1.718	1.708
8.8 – 9.2	1.696	1.686
9.2 – 9.6	1.674	1.664
9.6 – 10.0	1.650	1.640
> 10.0	1.470	1.470

The Lower Waveguide Cladding LWCL **2110** is made up of silica with a refractive index of n_{LWCL} = 1.47. The Upper Waveguide Cladding UWCL is made up of silica with a refractive index of n_{UWCL} = 1.47. The Side Waveguide Cladding SWCL is made up of lead silica-titania with a refractive index of distribution given in Table III.

For the case of a laterally up-tapered Waveguide Core WC **2145,** the dimensions of the WC are as follows: $l_{HRCSWCa}$ = 110 μm, $t_{HRCSWCa}$ = 0.3 μm, $l_{HRCVTDWCa}$ = 30 μm, $t_{HRCVTDWCaSB}$ = 0.3 μm, $t_{HRCVTDCaLB}$ = 0 μm, $l_{HRCSWCb}$ = 10 μm, $w_{HRCSWCb\cdot}$ = 0.3 μm, $l_{HRCLTUWCb}$ = 100 μm, $w_{HRCLTUWCbSB}$ = 0.3 μm, $w_{HRCLTUCbLB}$ = 10 μm, $l_{HRCWSWCb}$ = 30 μm and $w_{HRCWSWCb}$ = 10 μm. The dimensions of the Lower Refractive index Contrast Waveguide

Core LRCWC **2155** are as follows: $l_{LRCWC} = 170$ μm, $w_{LRCWC} = 10$ μm, $t_{LRCWC} = 10$ μm. The Lower Waveguide Cladding LWCL **2110** has a length of $l_{LWCL} = 170$ μm, a width of $w_{LWCL} = 30$ μm and a thickness of $t_{LWCL} = 2$ μm. The Upper Waveguide Cladding UWCL **2160** has a length of $l_{UWCL} = 170$ μm, a width of $w_{UWCL} = 30$ μm and a thickness of $t_{UWCL} = 2$ μm. The two side waveguide claddings SWCL **2176b** have a length of $l_{SWCL} = 170$ μm, a width of $w_{SWCL} = 10$ μm and a thickness of $t_{SWCL} = 10$ μm.

For the case of a laterally down-tapered Waveguide Core WC **2150,** the dimensions of the WC are as follows: $l_{HRCSWCa} = 10$ μm, $t_{HRCSWCa} = 0.3$ μm, $l_{HRCVTDWCa} = 30$ μm, $t_{HRCVTDWCaSB} = 0.3$ μm, $t_{HRCVTDCaLB} = 0$ μm, $l_{HRCSWCb} = 10$ μm, $w_{HRCSWCb\cdot} = 0.3$ μm, $l_{HRCLTDWCb} = 30$ μm, $w_{HRCLTDWCbSB} = 0.3$ μm, $w_{HRCLTDCbLB} = 0$ μm. The dimensions of the Lower Refractive index Contrast Waveguide Core LRCWC **2155** are as follows: $l_{LRCWC} = 70$ μm, $w_{LRCWC} = 10$ μm, $t_{LRCWC} = 10$ μm. The Lower Waveguide Cladding LWCL **2110** has a length of $l_{LWCL} = 70$ μm, a width of $w_{LWCL} = 30$ μm and a thickness of $t_{LWCL} = 2$ μm. The Upper Waveguide Cladding UWCL **2160** has a length of $l_{UWCL} = 70$ μm, a width of $w_{UWCL} = 30$ μm and a thickness of $t_{UWCL} = 2$ μm. The two side waveguide claddings SWCL **2176c** have a length of $l_{SWCL} = 70$ μm, a width of $w_{SWCL} = 10$ μm and a thickness of $t_{SWCL} = 10$ μm. It should be appreciated by one skilled in the art that all parameter values used in this and other exemplary embodiments are approximate and that the actual values can vary significantly.

(ii) General Operation of the Device

FIG. 41 shows the results of a computer simulation of the spatial distribution of the electric field strength in the vertical direction for light input from either direction at $\lambda = 1.5$ μm. The upper graph shows the behavior when light is input into the small light beam input/output port **2171a**; The mode size at input/output port **2171a** is 0.3 μm in the vertical direction. As the tapering down section only lies towards the right for the last 30 μm and the cascading beam expansion action occurs on both the left and the right part of the vertical WC taper tip, the computer simulation is thus zoomed into the last 60 μm of the coupler structure. The lower graph is similar. It shows the behavior when light is input to the large light beam output/input port **2177**. Comparing the two graphs demonstrates that the device has good coupling efficiency in both directions.

The beam expansion in the lateral direction for the laterally tapered up and laterally tapered down cases are similar to what has been described for exemplary devices 7 and 8 respectively; these cases are not shown in Fig. 41.

As can be seen from FIG. 41, the combined module coupler structure can transform a very small beam of about 0.3 μm in size to a large size beam of about10 μm in both the vertical and the horizontal directions. Very efficient bi-directional coupling is thus made possible by the supercoupler.

(iii) Device Fabrication Procedures

An exemplary procedure for fabricating a VSDT+NSVGRIN ICMT device **2100** will now be described with reference to Fig. 42A-N. This procedure is given for the purpose of illustration and not limitation, as there are other procedures that can be used to achieve the same fabrication results and other materials systems or device structures that can be utilized to fabricate devices with the same functional capabilities.

The VSDT+NSVGRIN ICMT may be fabricated by starting with a Silicon-On-Insulator (SOI) wafer, as shown in Fig. 42A, which may be fabricated via a commercial process known to those skilled in the art. For an SOI wafer, a silicon layer **2105** is already made on an insulating SiO_2 **2110** which is on top on a silicon substrate **2115**. The fabrication of the VSDT+NSVGRIN ICMT structure according to one embodiment is now described .

A Si taper may be fabricated by spin-coating a photoresist layer **2120** on the Si waveguide layer **2105**, as shown in Fig. 42A. A mask pattern with a gray scale transparency along the longitudinal direction and also a laterally tapered up pattern **2125**, as shown in Fig. 42B, or a laterally tapered down pattern **2130**, as shown in Fig. 42C, can be used together with UV exposure and photoresist development to make a tapered photoresist pattern that is vertically tapered down and laterally tapered up (pattern **2135** in Fig. 42D) or down (pattern **2140** in Fig. 42E). Followed by dry etching, indicated in Fig. 42F, the tapered photoresist pattern **2135** or **2140** may be transferred to the high refractive index Si layer and form the corresponding Si section **2145** or **2150**, shown in Fig. 42G-I. The interface between the top Si layer and the lower SiO_2 layer may be used as a natural stop during the dry etching process. A shadow mask based dry etching or a diffusion-limited wet etching may also be used to form the Si taper.

To form the top half of the vertically GRIN waveguide **2155**, multiple layers of effective refractive-index-decreasing dielectrics may be deposited on top of the Si taper, as

shown in Fig. 42J. Preferably photosensitive silica is spin-coated so that confinement of light in the horizontal/lateral direction may be easily achieved using UV imprinting. On the very top, a relatively thick (say 2 μm) silica layer **2160** may be deposited to act as an upper cladding.

As has already been discussed, to form a dielectric channel waveguide with either a GRIN or step refractive index distribution in the lateral direction to confine light propagation, UV imprinting may be used as the deposited vertically GRIN film can be made photosensitive. In this respect, a step channel mask **2165**, as shown in Fig. 42K, or a GRIN channel mask **2170**, as shown in Fig. 42L, may be used to form a single-mode step channel waveguide **2185**, as shown in Fig. 42M, or GRIN channel glass waveguide **2190**, as shown in Fig. 42N, to confine light in the horizontal/lateral direction.

One skilled in the art will recognize that high efficiency coupling from the buried GRIN channel waveguide to a single mode optical fiber or vice versa is not a problem as the mode size is already designed to match that of a single mode fiber. The chief consideration is the location for this joining. Preferably, the fiber is made to butt-join the GRIN channel waveguide at a fully expanded/collimated location rather than a focused location. The fiber is also preferably located at the first fully expanded location from the tip of the Si taper, in order to reduce light propagation losses in the glass channel waveguide.

It should be understood that the above dimensions and exemplary lengths are presented for the purposes of illustrating a useful embodiment of the device **2100** and are not intended to limit other embodiments of any exemplary device, or the device **2100**. A variety of dimensions and sizes can be used, depending on the application desired, as well as the fabrication materials, processes and technologies that are employed.

Also, it should be understood that the shapes of the waveguides or the taper (for example the shapes as defined by the surfaces dividing the cladding regions and the core regions) do not generally have to be linear or in the form of straight lines and planar surfaces. Curved shapes and different waveguide dimensions may be utilized as long as they achieve the same functions such as waveguiding or optical mode size transformation with similar topological connections. This applies for all the surfaces of the waveguide structures of the various embodiments of the present invention, including the side surfaces, the top and bottom surfaces, and the input/output surfaces.

In addition, it should be understood that the substrate is used to mechanically support the waveguide structures, and can be made up of irregular shapes, or structures, or

materials as long as it serves the function of providing mechanical support for the waveguide structures.

Furthermore, it should be understood that the output ports can also be used as input ports and the input ports can be used as output ports. This is due to the reciprocal nature of light propagation in passive optical devices and hence the bi-directional nature of the devices.

It should be understood to those skilled in the art that the device **2100** can be fabricated on a different substrate other than a silicon substrate. In particular, it can be fabricated directly on InP or GaAs substrates used for making semiconductor photonic devices or integrated circuits and may be fabricated directly at the input/output ports of the photonic devices by sharing the same substrate as the photonic device.

(10) VARIATIONS OF EXEMPLARY DEVICES AND INTEGRATION OF ICMT WITH V-GROOVES FOR FIBER ALIGNMENTS PLATFORM FOR PHOTONIC CHIPS

In the above mentioned exemplary combined module ICMTs that involve connecting a vertical sharp-down-taper waveguide core with a lower-refractive-index-contrast vertically graded waveguide, only two cases of placing the taper in the GRIN waveguide have been discussed, namely at the center of a symmetric GRIN waveguide or at the bottom of a half-GRIN waveguide. One skilled in the art will recognize that the GRIN waveguide need not to be restricted to these two cases. For example, the GRIN waveguide may have a refractive index distribution that is similar to the bottom half of a symmetric GRIN profile, and the taper can then be fabricated near the top of the GRIN waveguide. As another example, the GRIN waveguide can be three quarters of a symmetric GRIN profile; as long as the taper is fabricated near the high-refractive-index region of the GRIN profile, cascaded light beam expansion or reduction can be achieved. In fact, the GRIN waveguide may have an arbitrary profile, and the taper may be placed within a relatively large tolerance around the high-index region of the GRIN profile. FIG. 43 shows the structure and simulation results of light coupling from either side to the other. Note that compared to device **2100** of FIG. 40A, the Si taper **2210** is now shifted upward into the GRIN region **2220** and is buried above the lower cladding SiO2 layer **2230**. It can be seen that the while the taper to the half GRIN waveguide coupling is basically not changed as compared to the previous case, there is a slight increase in the reverse direction light coupling efficiency.

In terms of device fabrication, a silicon waveguide layer may be bonded on top of an X-SiO_2-Si structure illustrated in FIG. 44A. X may be a dielectric thin film **2310**

with a refractive index equal to the GRIN waveguide core. SiO_2 layer **2320** is a lower cladding layer for the GRIN glass/polymer waveguide, and Si layer **2330** is the substrate. The structure can be easily achieved by, for example, sputtering a glass film **2310** on the SiO2-Si wafer **2320/2330**. An ion-implanted silicon wafer with a structure of Si layer **2340** on ion-implanted layer **2350** on Si **2360**, shown in Fig. 44B, can be flipped over and bonded with the X-SiO2-Si wafer. Si layer **2360** is lifted off as discussed previously, leaving the structure shown in Fig. 44C. The rest of the fabrication steps are similar to those described above for exemplary device 9, beginning with fabrication of a tapered waveguide core in Si layer **2340**.

With respect to the various combined module ICMTs, at least three basic vertical structure configurations may be manufactured. While the symmetric GRIN waveguide structure offers the best coupling efficiency, it is the most challenging structure to fabricate as there is a need to bond an ion implanted Si wafer to a GRIN dielectric coated SiO_2-Si wafer. However, it should be understood that the sol-gel spin-coating approach described above is only one exemplary way to fabricate such a structure; modifications of the fabrication process can be made that may simplify the fabrication process. For example, instead of using the sol-gel technique described above, any other thin film deposition technique including flame hydrolysis, sputtering, Ion-Assisted Deposition, evaporation and chemical vapor deposition may be used to deposit the graded refractive index layers. As a result, the wafer-bonding can be relatively easily done as long as the bottom half of the GRIN waveguide is of high quality.

One preferred technique for simplifying fabrication is to first deposit a relatively thin dielectric film having a refractive index about equal to that of the GRIN waveguide core onto a SiO2-Si wafer before wafer bonding to an ion implanted Si wafer. For example, sputtering is a well-established process for depositing such films; as a sputtered film is relatively thin, it will be less challenging to wafer-bond an ion implanted Si wafer to a sputtered dielectric-SiO_2-Si wafer.

Another approach is to use a commercially available Si-SiO_2-Si or SOI wafer, make the top Si waveguide layer into a taper and spin-coat a half GRIN waveguide. Although the resulting light-coupling efficiency is slightly lower as compared to couplers with a full GRIN waveguide, the commercial availability of SOI wafers makes this a simple and easy option in terms of fabrication.

In terms of photonic chip mounting and optical fiber alignment with the couplers of the present invention, there are various options. Fig. 45A-C illustrates one process. After the formation of channel waveguides in the vertically GRIN glass waveguide

layer **2410** using, for example, UV imprinting, photolithography, as illustrated in Fig. 45A, can be used to define the Si V-groove wet etching opening **2420**. Selective dry etching of the GRIN glass waveguide layer **2410** and the insulating SiO_2 layer **2430** can then be employed to define a vertical wall **2440** in the GRIN glass waveguide layer, and Si V-grooves **2450** can be wet etched through the dry etched V-groove openings, as shown in Fig. 45B. To fabricate a photonic chip recess, another photolithography process can be carried out to define the recess/well opening **2460**. Dry etching can be carried out to etch the recess/well to a precise depth. Fig. 45C illustrates a section of the completed device. Metal contact pads **2470** as well as electrical conduction paths may be made by metal evaporation. Photonic chip **2480** may be mounted and soldered in the recess/well with slight heating to ensure good adhesion and electrical contact. The silicon wafer with the photonic chips attached and the Si V-grooves already made can be diced into small pieces. Subsequently, optical fiber arrays **2490** can be mounted in the Si V-grooves and fixed.

The process is readily adaptable to multiport devices, as illustrated in Fig. 46, where photonic chip **2480** may comprise one or more semiconductor optical devices connected by waveguides **2482** to multiport integrated couplers of the present invention **2484**. These devices, in turn, couple to optical fibers **2490**.

While the exemplary devices described above use a silicon substrate and a silicon based high refractive index taper, it should be understood that these materials are only meant to illustrate exemplary cases. The embodiments of the present invention also include the use of other suitable materials for the substrate and the high index waveguide core or taper, wherein these suitable materials include compound semiconductor based material such as gallium arsenide, indium phosphide and gallium nitride, or an optical crystal based material such as lithium niobate, lithium tantalate and barium titanate, or a dielectric material such high index glasses.

IV. Applications

The applications of the mode transformation couplers of the present invention are numerous as the technology addresses the bottleneck of the present photonic integrated circuit (PIC) technologies. Couplers are used in the pigtailing and packaging of almost all semiconductor and optical crystal based photonic devices, especially those with multi-function and multiple ports. One application is in optical communication, where a coupler can be used for the packaging of all kinds of semiconductor and optical crystal based devices including semiconductor lasers, modulators, switches, mulitplexers/demultiplexers,

amplifiers, power splitters and so on. Presently, there are a number of technologies that are producing these photonic devices, such as III-V-based OEICs, Si-based optical or photonic MEMS, SOI- and SiGe-based integrated optical systems. All these will need mode conversion couplers to link to each other and to the outside world.

Another application is the concept of a photonic breadboard on which different integrated photonic chips are mounted and interconnected to one another via couplers of the present invention as shown in Fig. 47. Such an optical breadboard can be used to construct a system and test its function or performance before a fully integrated system chip is fabricated.

Note that a future trend of photonics is in the integration of multiple functional components on the same chip with multiple input and output ports to be connected to fiber arrays. In addition to optical communication, these chips will basically do the work that today is done by microelectronics chips, but at a much faster speed than their electronic counterparts. It can thus be foreseen that the cost of each component will drastically drop through photonic integration, as has happened for semiconductor-based electronics. The couplers of the present invention together with the associated packaging technology provides a significant reduction in the overall cost of such a multi-port photonic chip. The application areas of these photonic chips are potentially very wide, encompassing, for example, processors, computers, sensors, etc.

The foregoing description has provided exemplary embodiments of multiport integrated couplers and processes for fabricating these exemplary devices; these examples are intended to illustrate and not to limit the scope of the invention. One skilled in the art will recognize that various modifications are possible. For example, the waveguides are described with reference to coupling with particular optical devices such as semiconductor optical devices and optical fibers. One skilled in the art will recognize that the utility of the waveguides according to the present invention is not limited to the particular devices mentioned herein; indeed, the waveguides may be used with any optical device, and the dimensions of the waveguides may be varied for optimal matching to the optical device. Therefore, the scope of the present invention should be determined by the following claims, including their full range of equivalents.